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PLANETARY EXPLORATION THROUGH YEAR 2000

AN AUGMENTED PROGRAM

PART TWO OF A REPORT BY THE SOLAR SYSTEM EXPLORATION COMMITTEE OF THE NASA ADVISORY COUNCIL

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PLANETARY EXPLORATION THROUGH YEAR 2000

Cover *Geologic map of the Olympus Mons region of Mars. This giant martian volcano is the largest known volcano in the solar system, rising 26 kilometers into the thin martian atmosphere from a base 650 kilometers wide.*

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WASHINGTON, D.C., 1986

Viking 2 *view of the south polar ice cap of Mars. The ice, which may be permanent, is composed mostly of carbon dioxide and may contain water as well.*

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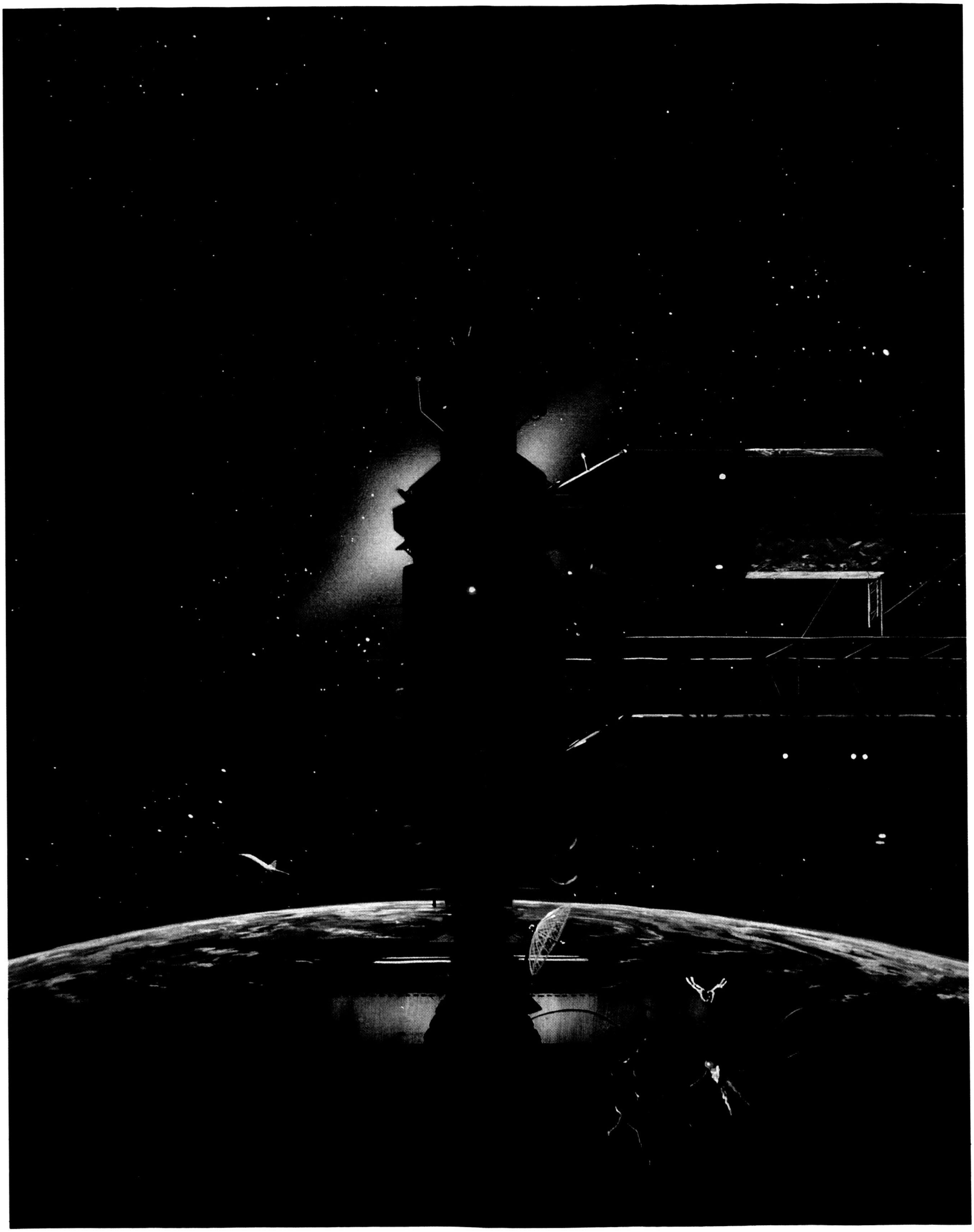
The permanent manned Space Station in its early stages of operation. The upper module of the Space Station eclipses the Sun, whose pearly coronal atmosphere is visible. Zodiacal light, reflected off dust in the plane of the solar system, stretches to the upper right and lower left.



EXECUTIVE SUMMARY

The exploration of space is one of the great adventures of humanity. Our generation is making its permanent mark on history by pushing back the frontiers of knowledge and human experience to include Earth as a planet and its neighboring worlds in the solar system. The exploration of distant planets using robotic spacecraft has, like the manned space program, been an achievement almost in the realm of fantasy. But this continuing exploration, a source of wonder to the entire world, is no dream—it is an extraordinary technical and scientific adventure in which the entire nation can take pride. For the past two decades, the United States has led the way in this enterprise, to the lasting benefit of all peoples.

In 1982, the NASA Solar System Exploration Committee (SSEC) published a report on a *Core Program* of planetary missions, representing the minimum-level program that could be carried out in a cost-effective manner, and would yield a continuing return of basic scientific results. This is the second part of the SSEC Report, describing missions of the highest scientific merit that lie outside the scope of the previously recommended Core Program because of their cost and technical challenge. It is this challenge, as much as the scientific rewards, that will serve to maintain U.S. preeminence in space exploration. The missions recommended here will also play an essential role in bridging the gap from our present level of knowledge to the broader goals for space exploration envisioned for the next century by the U.S. National Commission on Space, which are being reported as this SSEC Report goes to press.

The missions recommended in this report could readily be undertaken in the next decade, at a cost less than that associated with planetary missions during the early 1970s. **The SSEC strongly recommends that they *should* be undertaken in that time frame.** This report summarizes the scientific justification for these missions and identifies the new technologies whose development is needed to make them possible. Only if we accept these challenges to develop new technologies, and to pursue the exploration programs so nobly begun during the past two decades, will we be able to continue to contribute to the objectives of understanding our planetary system and preparing the way for humans to eventually live permanently in space and on the Moon and Mars.

The Core Program

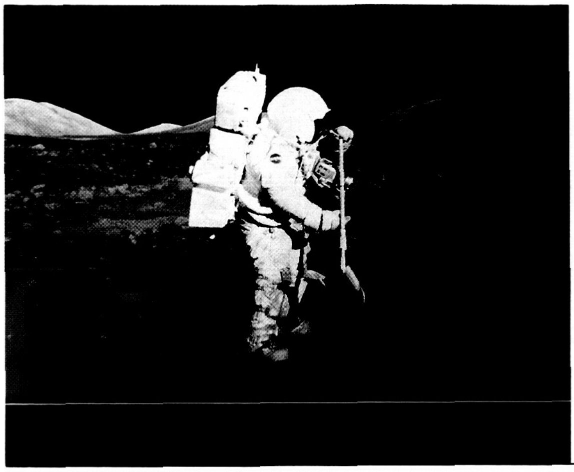
In this volume, **"Beyond the Core Program"** (Chapter 1) reviews the circumstances in which the SSEC was formed and summarizes the main aspects of its recommended Core Program. The SSEC was established in 1980 in response to a widespread concern about the future of planetary exploration. The previous years had been characterized by erratic funding, increasingly constrained budgets, higher mission costs, and longer intervals between approved missions. Consequently, there developed real concern in the early 1980s about the very survival of the U.S. planetary exploration program. The SSEC was called on to devise an appropriate strategy for planetary exploration up to the year 2000.

Part I of the SSEC Report is a detailed description of the scientific potential of future solar system exploration and of the type of program needed to realize it.

The Core Program recommended by the SSEC establishes a continuing, although cost-constrained, effort of exciting planetary exploration that will continue to break new ground, including the first in-depth exploration of the comets and asteroids. This program is scientifically balanced; it carries out frontier scientific studies of the three main types of solar system objects: terrestrial (inner) planets, gas-giant (outer) planets, and small bodies (comets and asteroids). It *requires* no new technology (but will take advantage of new technologies as they become available) and includes the use of spacecraft adaptable for different missions. Finally, the program is time-phased to permit stable funding of about $325 million (FY 1984 dollars) per year, an efficiency that would save resources and reduce the increasingly intolerable risks of the "feast-or-famine" budgeting that had characterized the previous period of planetary exploration.

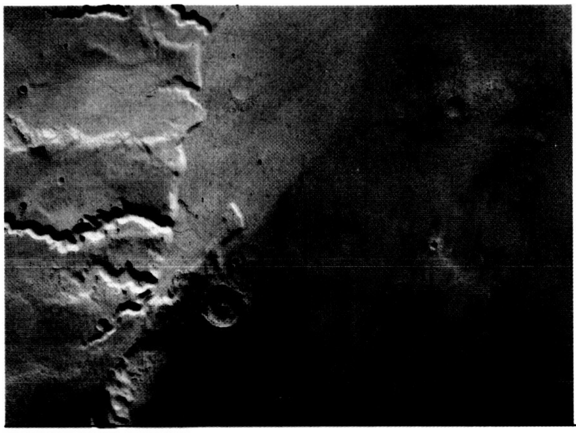
Inevitably, because of the fiscal constraints of the Core Program, a number of exciting and scientifically compelling missions have been excluded from it. Most notable, because of cost and technological requirements, are missions involving sample returns and roving vehicles on planetary surfaces.

Among the principal past benefits arising from space exploration have been the new products and technologies developed from the need to meet major technological challenges. **In recognition of this fact, the SSEC urges that the Core Program be augmented, as soon as possible, by missions that will drive technology in the name of bold scientific exploration.** Such Augmentation Missions would serve to keep alive the spirit and vigor of this nation at a time when the United States is losing its monopoly of cutting-edge space capabilities. The nature and challenges of these Augmentation Missions are the subjects of this report.



Sample Return Missions

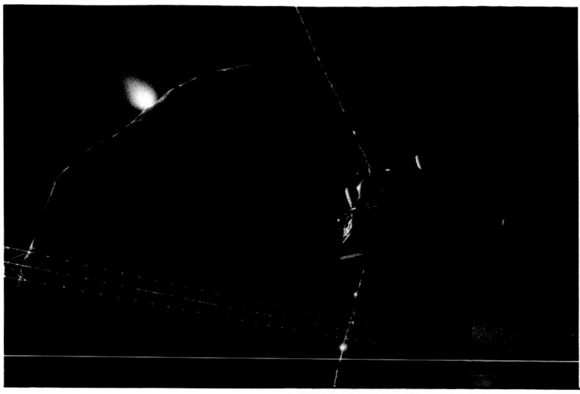
The **collection and return of samples from other worlds** by automated spacecraft for analysis in terrestrial laboratories is potentially the most powerful technique for extending our understanding of the solid bodies in the solar system: inner planets, asteroids, and comets. **"The Long Reach"** (Chapter 2) describes, in general, the importance of such missions. Returned samples provide unique and, in practice, otherwise unobtainable information about the worlds from which they come: **chemical compositions, physical properties, ages, and interactions with the space environment.** Moreover, the independent age measurements made on such samples make it possible to establish the timing of the origin and historical development of other worlds and of the solar system itself. The achievements arising from the analysis of extraterrestrial samples (moon rocks, Antarctic and other meteorites, cosmic dust particles) have provided a solid base of experience from which the collection, protection, and analysis of future returned samples can be planned in detail.



Target: Mars

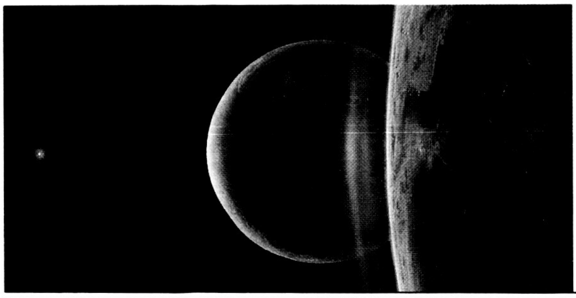
A sample return mission to Mars before 2000 is the highest priority for an Augmentation Mission to the terrestrial planets. Mars is now an appropriate and attainable target, and **"A Handful of Mars"** (Chapter 3) explains why a sample return mission to Mars is timely, logical, and feasible. Mars is the most Earthlike planet in the solar system. (It is also the only other planet likely to support human habitation.) In terms of planetary evolution, Mars spans the gap between relatively primitive worlds like Mercury and the Moon and highly evolved planets like Earth.

As a legacy from our previous missions to Mars, there is already an adequate data base available to make a sample return mission possible and to appreciate the depth of the exciting science information that would be forthcoming. The mission described here uses a surface roving vehicle to collect and document as wide a range of samples as possible. The mission itself calls for the application of robotics technologies that lie within our grasp. It would be highly visible, like *Viking,* and exciting to scientists and the public alike, particularly because of the literally new horizon that would be made accessible each day through the lander's mobility. **The combination of the interest in Mars, the various new technologies (robotics, mobility, and aerocapture to replace chemical propulsion for Mars orbit insertion), and the breakthrough science makes this mission as exciting as any that NASA has undertaken in its history.**



Target: Comet

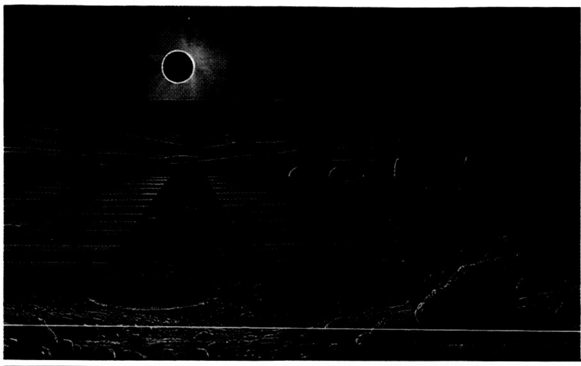
A sample return mission to the nucleus of a comet is the highest-priority Augmentation Mission to study the small bodies of the solar system. Comets are especially important because they are probably made up of the least-altered material from which the solar system formed. **"A Piece of Creation"** (Chapter 4) explains why **a sample return mission to a comet is an essential step in the search for clues to the beginning of the solar system, to the relations between the solar system and interstellar space, and perhaps to the origins of life itself.** The recently obtained images of the nucleus of Comet Halley provide a sense of why landing on such a body and bringing a piece back to Earth for analysis would be uniquely exciting and demonstrative of the nation's technological genius. The *Comet Rendezvous/Asteroid Flyby* mission of the Core Program will provide sufficient data to successfully execute a sample return. Current information is already adequate to define the scientific goals for the mission, to define the required approach, and to identify the technologies (especially low-thrust propulsion) whose development is needed to make the mission possible. The high level of interest in this mission in the European space science community makes comet nucleus sample return a likely candidate for international collaboration.



The Outer Worlds

It is at present too early to identify a single Augmentation Mission, or even a class of missions, to the giant planets and moons of the outer solar system. Despite the exciting strangeness and diversity of these worlds, still being revealed by the *Voyager* missions, **the data base for planning future missions must be increased before specific missions and targets can be identified.** The necessary data will be provided by the more complete analysis of the *Voyager* data set, by the approved *Galileo* mission to Jupiter, and by the *Cassini (Saturn Orbiter/Titan Probe)* mission in the Core Program.

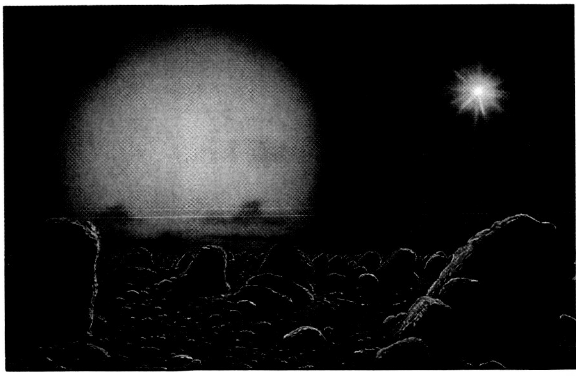
"The Realm of the Giants" (Chapter 5) explains why continued study of these worlds is essential to understand the solar system. These giant planets contain almost all of the mass of the solar system outside of the Sun, and they display huge magnetic fields, complex and beautiful ring systems, and baffling varieties of moons that range between the extremes of fire and ice. Some types of Augmentation Missions that might be undertaken in the future are suggested: combined orbiter/probes, long-lived atmospheric probes, and surface landers. Even though such missions belong to the years beyond 2000, essential technical developments must be started now to make them possible. A prime need is improved propulsion systems to reduce the long travel times involved.



Bonanza in Space?

Planetary science, and planetary exploration activities, have a fundamental role to play in making it possible to use near-Earth resources (from the Moon and nearby asteroids) to support future human activities in space. As other advisory groups have pointed out, large-scale human activities in space will, in time, become an integral part of Earth's economy. The use of near-Earth resources, obtained from the Moon and nearby asteroids, will be essential. The ability of the U.S. to be prepared to act, when the time comes, depends on our preparedness, including having in hand a scientific survey of the resources that are potentially available in space.

In **"The Riches of Space"** (Chapter 6), the SSEC describes briefly the nature of potentially available resources (lunar soil and asteroidal material) and discusses the benefits that such resources could provide (including shielding and oxygen). Since our current information is not adequate to make any intelligent decision at this time about the future use of near-Earth resources in space, more information must be obtained. Several important areas are identified for further effort: future missions (such as the Core Program's *Lunar Geoscience Orbiter*), ground-based laboratory studies and technology demonstrations, and studies of various space systems using near-Earth resources for their construction and maintenance.



Other Worlds?

In the last few years it has become possible to make a rigorous search for planets around other stars, a search which will effectively open up a whole new area of science. The SSEC strongly recommends that such a search should go forward, augmenting limited ground-based methods by applying telescopes attached to the planned Space Station.

The long-debated question about whether planets exist around other stars has taken on a new dimension in the last few years. Theories of solar system formation have become advanced enough to predict the general existence of planets, and ground-based observations, following up the first space infrared sky survey, have discovered what may be a planetary system in the early stages of formation.

"Beyond the Solar System" (Chapter 7) reviews the theoretical evidence that solar systems are common and describes some of the observations that indicate the existence of planets (or at least planet-like objects) around other stars. Long-term searches for other planets can be undertaken with a variety of space-based techniques that can detect, possibly even image, the worlds around other stars. The planned Space Station will make a highly effective base for the mounting of instruments dedicated to such searches.

This search, even in the unlikely event that it provides evidence of our own solar system's uniqueness in the universe, will have a profound impact on both scientific theories and philosophical ideas about our place in the universe. If planets are common, then our theories are good, and life (and intelligent life) may be common in the universe. If planets are rare, our theories are in serious trouble, and humankind must face the possibility that we are alone in the universe.

New Tools

None of the proposed Augmentation Missions, nor any other of the activities discussed in this volume, can be carried out with currently available technology. The technical challenges presented by these missions and activities will require developments in a wide range of frontier technical fields: propulsion, automatic roving vehicles, robotics, and rugged instrument components. **The benefits of new developments in these fields will extend far beyond the planetary program.**

These challenges are regarded by the SSEC as one of the major benefits of these missions, and **"New Tools for New Worlds"** (Chapter 8) describes briefly the kinds of technological developments that are required to make the missions possible. The robotics and mobility technologies that are needed will find an unusually challenging application. A particularly urgent need is for improved propulsion, to permit larger mission payloads and to reduce the travel times to distant planets. Possible solutions include: low-thrust propulsion (solar- or nuclear-electric), aerocapture techniques, and a variety of mission operations at the Space Station.

Recommendations

Specific recommendations are included at the end of each chapter. The most important recommendations of the SSEC are:

- **Sample return missions to Mars and to the nucleus of a comet are the highest-priority Augmentation Missions.** The necessary studies and technical developments should begin at once. The missions should be carried out as soon as possible.
- **The *Comet Rendezvous/Asteroid Flyby* (CRAF)** mission is an essential precursor to a sample return mission to a comet. *CRAF* should be carried out as soon as possible.
- **The highest priority for Augmentation Missions to the outer planets is to complete the necessary data base with the *Voyager 2*, *Galileo*, and *Cassini* missions.** In the meantime, studies of possible missions, and especially the development of enabling technologies, should go forward as rapidly as possible.
- **The ground-based planetary science research effort should be strengthened.** Such activities (especially supporting research, ground-based observations, and data analysis) are essential ingredients of the Core Program. They should be expanded by adding activities relevant to the proposed Augmentation Missions and related activities: specific mission studies, research and data analysis involving Mars, comets, and the Moon, resources-oriented analyses of available extraterrestrial materials, and telescopic observations of near-Earth asteroids.
- **Major technological developments in a wide range of fields should be begun at once in order to make the Augmentation Missions possible within the next ten to 15 years.** Such generic developments as propulsion, aerocapture, surface mobility, sample handling, and robotics are especially urgent and affect virtually all the activities discussed here: sample return missions, outer planet missions, and near-Earth resources use. Improved propulsion (possibly solar- or nuclear-electric) is a special need and should be given special emphasis. Other developments, related to specific mission needs (remote sample handling), should also be supported.

The Space Station

The SSEC study was in its final stage in January, 1984, when President Reagan made the national commitment to establish a Space Station in the mid-1990s. Therefore, the SSEC was not able to consider in detail the possible effects of the Space Station on its recommended activities. However, the SSEC has noted in various places in this volume that **the Space Station could play a major role in supporting several of the recommended activities,** for example, sample return missions, an astrometric search for other planetary systems, and other types of planetary astronomy.

It is essential that the role of the Space Station in planetary science be examined in more detail, and the SSEC notes with satisfaction that several such studies are now being carried out by advisory groups supported by the National Academy of Sciences and the NASA Advisory Council.

The Critical Need for the Core Program

The most urgent priority for the continued health of the U.S. planetary exploration program is the timely establishment and continued support of the Core Program defined in Part I of the SSEC Report.

The SSEC has noted with pleasure the positive developments in this direction that have occurred since Part I of its report appeared in 1983. These include the approval of the *Venus Radar Mapper (Magellan)* as an FY 1984 new start mission and the subsequent approval of the *Mars Observer* in FY 1985. Equally important has been the increased support of the Planetary Research and Analysis area, which, if it has not exactly reached the (adjusted) FY 1981 level recommended by the SSEC, has at least come close to this goal.

However, the SSEC is disturbed at the delay in the establishment of the first *Mariner Mark II* mission, the *Comet Rendezvous/Asteroid Flyby (CRAF).* **The early development of the modular *Mariner Mark II* spacecraft is essential for making possible the recommended Core Program Missions to the entire outer solar system and to comets.**

The first two recommended *Mariner Mark II* missions, CRAF and *Cassini (Saturn Orbiter/Titan Probe)*, are targeted toward objects of special scientific importance. Equally important, these two missions have an important role in completing the data base upon which all Augmentation Missions to comets and to the outer solar system must be based.

The first *Mariner Mark II* mission (CRAF) should be instituted as soon as possible. Further delay in this essential step will cripple the exploration of the outer solar system, will create a critical imbalance in the recommended Core Program, and will delay the acquisition of information on which some of the most essential and exciting Augmentation Missions must be based.

Furthermore, there still remains a need for continuing support for Planetary Research and Analysis Activities. The current levels must be maintained, and modest increases should be provided for tasks and studies essential to the Augmentation Missions discussed here.

The Years Ahead

Part II of the SSEC Report was virtually complete on January 28, 1986 when the *Space Shuttle Challenger* and its crew were lost in an explosion shortly after liftoff. This tragedy was twofold: first, the loss of the crew and the spacecraft, and second, the resulting delay for all space science missions.

In reviewing Part II in the light of this disaster, the SSEC does not feel that changes in its Report are necessary. Despite the tragedy and the resulting setbacks, the science goals remain unchanged. The importance of the proposed studies remains as great as it was. The priorities established for the specific missions, and for the technical developments they need, are unaltered.

The SSEC feels that both the scientific justification for planetary exploration and the recommendations that it has presented in Parts I and II of its Report remain sound, and the priorities are not affected by the *Challenger* tragedy. In its Report, the SSEC has described a series of missions and activities that must be carried out in order to continue the quest for knowledge about the solar system. These missions and activities, and the SSEC's recommendations about them, are largely independent of schedule changes or the availability of specific launch vehicles.

In short, the SSEC's view remains: these Augmentation Missions should be done, and they should be done as soon as possible, in the order of priority that the SSEC has assigned to them. It is perhaps especially important, at this time of general uncertainty and concern, to establish a firm commitment to the Core Program and the Augmentation Missions, in order to place the U.S. planetary exploration program on a sound and enduring basis.

The U.S. planetary exploration program, not yet 25 years old, will stand in the history of humanity as a major human and national achievement. It is hard to find events to compare it to; not since Galileo has our picture of the solar system–and our place in it—changed so drastically in so little time. Distant worlds have become familiar landscapes. New worlds–mysterious and often totally unpredictable–have been revealed. And from exploring other worlds, we have come to better understand our own.

From planetary exploration, the whole human race has obtained a glimpse of new frontiers, a better understanding of its solar neighborhood, and a new appreciation of how its own planet works. A new generation of scientists is growing up with the potential to plan and carry out investigations that were impossible a generation ago–close examination of rocks from Mars, laboratory analyses of ancient ices from a comet, and the launching of more sophisticated and capable spacecraft to distant and still-unknown worlds. The planetary exploration program has provided all of us with excitement, knowledge, answers to old questions, new questions to answer, and even stranger mysteries than we had thought possible.

In the various volumes of its Report, the SSEC has outlined a program of planetary exploration that can become an important national activity: visible, exciting, scientifically important, technically challenging (but not impossible), publicly and nationally inspiring, and easily affordable.

The SSEC strongly urges that this program go forward as fast as possible. Nothing could better commemorate the coming 25th anniversary of planetary exploration in 1987 than to make a commitment to a new generation of planetary exploration that can carry us to the year 2000 and into the millennium beyond.

Fiery entry of the Saturn Atmospheric Probe *into Saturn's atmosphere.*

1. Beyond the Core Program

AN INTRODUCTION TO PART II OF THE SSEC REPORT

The SSEC Is Formed

The 20 years between *Mariner 2*'s first flyby of Venus in 1962 and *Voyager 2*'s final encounter with Saturn in 1981 will always be remembered as the Golden Age of planetary exploration. During this exhilarating time, robot spacecraft were launched every few months, first to the Moon, then further outward to Venus and Mars, and finally to every planet known to ancient peoples, from Mercury to Saturn. At the same time, human beings left their own world, walked on the surface of the Moon, and returned safely to Earth. Suddenly, within less than a generation, humans explored more than two dozen new worlds and began to see their own planet in its true cosmic context for the first time.

This period of intense space exploration generated an unprecedented flood of exciting discoveries and new scientific knowledge about our universe. These efforts also created a sense of optimism and a recognition of the potential for long-term human activities in space. Manned missions like *Apollo* had established that humans could enter space, survive, and return safely. They could live and work in space for long periods, building things, operating instruments and machines, and carrying out scientific research. At the same time, unmanned missions had provided a totally new picture of the solar system and the universe and had given us global characterizations of most of the planets. We had gathered a solid base of scientific data and a host of tantalizing new questions about other worlds, and we were ready to begin the systematic and detailed exploration of the solar system.

But in the late 1970s, despite the achievements of the space program in exploring the solar system, the budgets for NASA's space science activities became increasingly constrained, the rate of new starts for planetary missions was reduced, larger gaps in time appeared between missions, and it became difficult to maintain the momentum and efficiency of earlier years.

Against this background of increasing concern about the future of the nation's planetary exploration program, Dr. Thomas A. Mutch, NASA's (then) Associate Administrator for Space Science, recommended in 1980 that NASA undertake a fundamental review of the entire planetary program by an advisory committee of involved scientists and engineers. As a result, the Solar System Exploration Committee (SSEC) was created as a subcommittee of the NASA Advisory Council in the fall of 1980 by (then) Administrator Robert Frosch. The charter of the SSEC read, in part:

"...translate the scientific strategy developed by COMPLEX [The National Academy's Committee on Planetary and Lunar Exploration] into a realistic, technically sound sequence of missions consistent with that strategy and with resources expected to be available for solar system exploration. The Committee will focus its initial efforts on those missions planned for initiation in FY 1984 and then extend its consideration as far into the future as possible, certainly as far as 1995..."

Goals and Recommendations

To provide a framework for its recommendations, the SSEC endorsed four general goals for solar system exploration:

- To determine the origin, evolution, and present state of the solar system (the primary goal).
- To understand Earth through comparative planetary studies.
- To understand the relationship between the chemical and physical evolution of the solar system and the appearance of life.
- To survey the resources available in near-Earth space (a new goal).

Plans for the Planets

The general scientific strategy for future planetary exploration has been established in a series of studies published by the Committee on Planetary and Lunar Exploration (COMPLEX). These studies presented the general goals and principles that have governed subsequent planetary exploration of specific classes of targets: the terrestrial planets, the outer planets, and the primitive bodies (comets and asteroids).

A key concept is the recognition of three different stages of planetary exploration, *Reconnaissance, Exploration,* and *Intensive Study.* Each of these stages is carried out by different, and increasingly sophisticated, missions. The stages, and their characteristics, are:

Reconnaissance:

- Initial stage of planetary exploration.
- Major characteristics of the planet sought out and identified.
- Typical missions: *flybys* (Mariner, Pioneer, Voyager missions at Uranus and Neptune); *hard-landers* (original Ranger missions to the Moon).
- **Goal:** To provide enough information about the planet and its environment to proceed to the next step (*Exploration*).

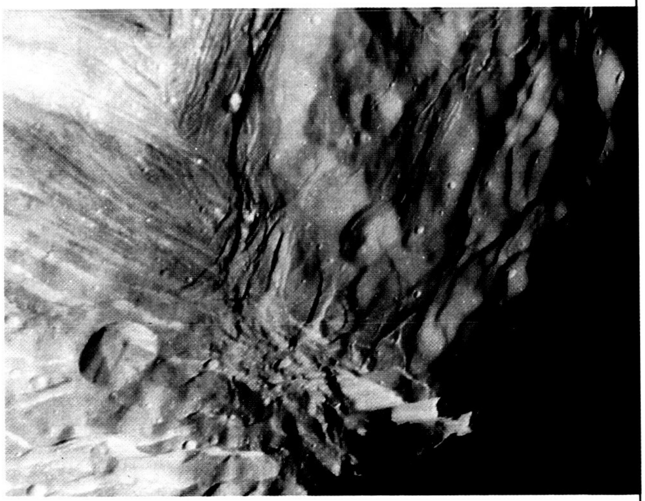
Exploration:

- Generally based on *Reconnaissance* stage.
- Involves systematic discovery and understanding of processes, history, and evolution of planet *on a global scale.*
- Typical missions: *orbiters* (Lunar Orbiter, Mariner 9, Galileo); *atmospheric probes* (Pioneer Venus); *penetrators.*
- **Goal:** To establish a global data base of planetary information in order to support future *Intensive Study* missions.

Intensive Study:

- Should be based on adequate *Reconnaissance* and *Exploration* missions.
- Attacks specific problems of high importance that are formulated in depth. May involve concentrated studies in local areas.
- Highest level of planetary exploration established by COMPLEX.
- Typical missions: *soft landers* (Surveyor, Viking, U.S.S.R. Venera); *surface rovers* (U.S.S.R. Lunakhod); *atmospheric balloons* (U.S.S.R. VEGA); *unmanned sample return* (U.S.S.R. Luna); *manned landings* (Apollo).
- **Goal:** To obtain detailed, in-depth knowledge about specific high-priority planetary problems.

***Close-up* Voyager *image of the complex surface of* Miranda, *the innermost major moon of* Uranus.**



The SSEC concluded that the most urgent priority was to stabilize the planetary exploration program while, at the same time, ensuring continued progress toward these goals. The SSEC therefore first formulated a Core Program of planetary exploration that was stable, produced exciting and important scientific results, made the maximum use of existing facilities and technologies, and could be carried out with a reasonable level of continued funding.

The SSEC also recognized that many essential, challenging, and scientifically rewarding types of planetary missions–sample return, surface rovers, and complex missions to the outer planets–could not be accommodated within the Core Program because of their technical complexity and cost. The SSEC therefore recommended that the Core Program be augmented as soon as possible by a number of missions (here called Augmentation Missions) which would combine higher scientific yields with major technical challenges. The Core Program plus the Augmentation Missions would together make up the Augmented Program of planetary exploration.

Finally, the SSEC recognized that certain topics–technology development, the use of near-Earth space resources, and the search for other solar systems–have important implications for planetary exploration both before and after the year 2000. The SSEC concluded that certain aspects of these areas need to be studied and developed now so that planetary exploration, both before and after 2000, can continue to develop at an adequate pace. For this reason, the SSEC included these subjects in its discussion of the Augmented Program.

The Core Program

The Core Program, and the recommendations for establishing it, were described in detail in Part I of the SSEC Report (*Planetary Exploration Through Year 2000: A Core Program*), which was published in May, 1983. This Core Program can be summarized as follows:

1. It is based on science strategies developed and updated by the Space Science Board (SSB) of the National Academy of Sciences through its Committee on Planetary and Lunar Exploration (COMPLEX).

2. In keeping with the COMPLEX strategy, it provides a balanced approach to solar system exploration by including near-term missions to a variety of targets: the terrestrial planets, the outer planets, and the small bodies (comets and asteroids).

3. It establishes the minimum level of flight mission activity that is necessary to maintain a healthy scientific program.

4. It is designed for a realistic, level, sustainable budget, so that long-term stability can be restored, both to the planning and implementation of new missions and to the associated research and data analysis.

The Core Program in Detail

In developing the Core Program, the SSEC provided specific recommendations about how it should be established. These involve targets of new planetary missions, development of new multi-mission types of planetary spacecraft, institution of new and more efficient techniques of mission operations, and strengthening of support for ground-based planetary research.

CRAF, ***first of the*** **Mariner Mark II** ***class of missions, approaching its rendezvous with an inactive comet nucleus.***

- An initial sequence of Core Program Missions should include the *Venus Radar Mapper* (now renamed *Magellan*), a *Mars Geoscience/Climatology Orbiter* (now renamed the *Mars Observer*), a *Comet Rendezvous/Asteroid Flyby,* and a *Titan Probe/Radar Mapper.*
- Future Core Program Missions should form a balanced group covering the three areas of the terrestrial planets, the small bodies (asteroids and comets), and the outer planets.
- A "Planetary Observer" Program should be established, consisting of low-cost, modestly scaled missions within the inner solar system.
- A "Mariner Mark II" Program should be developed, involving a straightforward modular spacecraft of the Voyager-Galileo class, capable of a variety of missions beyond the inner solar system.
- A common Mission Operations and Information System (MOIS) should be developed for all missions after the *Venus Radar Mapper (Magellan).*
- The Planetary Research and Analysis Programs should be significantly strengthened, in order to expand their capability to analyze currently available data, to perform necessary ground-based research, and to develop instrumentation for missions in the Core Program.
- Vigorous efforts should be made to seek mutually beneficial international cooperation in solar system exploration.
- Because there are major scientific objectives not capable of being addressed by the Core Program, this program should be augmented with technically challenging missions as soon as national priorities permit. Such Augmentation Missions, together with the Core Program, would constitute an "Augmented Program."

First of the **Planetary Observers,** *the* **Mars Observer** *passes high over the north polar region of Mars.*

The Core Program: The First Missions

The SSEC recommended that four specific missions be the first ones undertaken by the Core Program: the *Venus Radar Mapper* (now *Magellan*), a *Mars Geoscience/Climatology Orbiter* (now *Mars Observer*), a *Comet Rendezvous/Asteroid Flyby*, and a *Titan Probe/Radar Mapper*. These missions would establish at the beginning an exciting and balanced exploration program with targets selected from the three basic types of solar system objects: terrestrial planets (Venus and Mars), outer planets (Saturn and Titan), and small bodies (asteroids and comets).

Since the SSEC recommendations were published, the *Venus Radar Mapper (Magellan)* was approved as a new mission start in FY 1984 and has been scheduled for a 1988 launch. The *Mars Geoscience/Climatology Orbiter (Mars Observer)* was approved as a new mission start in FY 1985 and is now being developed for a planned 1990 launch. The *Comet Rendezvous/Asteroid Flyby (CRAF)* is under active study as a candidate new start mission in the near future. The *Titan Probe/Radar Mapper* is being studied as a possible joint mission, a *Saturn Orbiter/ Titan Probe*, which would be carried out in cooperation with the European Space Agency (ESA) under the name *Cassini*.

Details of these four missions are:

Magellan

Mission Description

The *Magellan* mission *(Venus Radar Mapper)* is scheduled to be launched in April, 1988 by the *Shuttle/Centaur* launch system. After cruising from Earth to Venus for about three and one-half months, *Magellan* will fire its Star-48 solid rocket motor to insert it into a near-polar, highly elliptical orbit of 300 by 8,000 kilometers around Venus. Radar mapping will be conducted for 30 minutes during the periapsis (low-altitude) portion of each orbit. The data will be played back to Earth during the outbound leg of the orbit. Mapping will be conducted for one venusian year (243 days), until at least 70 percent of the surface is mapped at one kilometer resolution and 90 percent of the surface is mapped overall.

Mission Goals

- Develop a near-global map of the surface of Venus using synthetic aperture radar imaging techniques that produce ground resolutions of better than one kilometer.
- Generate a global and local topographic profile of the surface with the radar altimeter with a vertical resolution of 100 meters and a horizontal resolution of 50 kilometers.
- Measure the global gravity field with a resolution of about three milligals.

Mission Status

- Congressional approval received in 1983 as an FY 1984 new mission start.
- Spacecraft and systems under development.
- Final spacecraft assembly and test operations scheduled for September, 1986.
- Projected launch date is April, 1988.

Mars Observer

Mission Description

The *Mars Observer* will be the first mission to use a *Planetary Observer* class spacecraft. The mission is planned to be launched in August, 1990, using the *Space Shuttle* and a Transfer Orbit Stage for the spacecraft. After a one-year interplanetary cruise to Mars, the spacecraft will be inserted into a circular, near-polar orbit with an altitude of 350 kilometers. For the next two months, the orbit will be allowed to drift until the desired Sun angle on the martian surface is achieved. The orbit will then be changed to place the spacecraft into a 93-degree sun-synchronous orbit. Mapping will continue for a period of one martian year (687 days), and data will be collected on the climatology, surface composition, topography, gravity field, and magnetic field of Mars. At the end of the mission, the spacecraft will be boosted to a higher quarantine orbit of 500 kilometers in order to prevent atmospheric entry before the year 2019.

Mission Goals

- Determine the global elemental and mineralogical character of the surface of Mars.
- Determine the time and space distribution, abundance, sources, and sinks of volatile materials and dust over a seasonal cycle.
- Define the gravitational field and topography on a global scale.
- Explore the structure and aspects of the atmospheric circulation of Mars.
- Establish the nature of the global magnetic field.

Mission Status

- Congressional approval received in December, 1984 as an FY 1985 new mission start.
- Currently in the early phases of development.
- Selection of investigations was made in April, 1986.
- Scheduled launch date is August, 1990.

Comet Rendezvous/Asteroid Flyby (CRAF)

Mission Description

The *CRAF* mission will be the first mission based on the *Mariner Mark II* class of interplanetary spacecraft. It is tentatively scheduled for launch in late 1992 aboard the *Shuttle/Centaur* launch system. After a six-month cruise period, the spacecraft will fly to within 6,000 to 10,000 kilometers of one or two Main Belt asteroids and will conduct investigations on composition and structure. *CRAF* will then proceed on its interplanetary trajectory for a rendezvous with a periodic comet, Tempel 2. Comet rendezvous will be achieved during the comet's quiescent period which occurs at a great distance from the Sun. Following the approach to the comet, the spacecraft will maneuver to within 25 kilometers of the comet nucleus and will begin close-in observations which will include shooting a penetrator instrument into the nucleus. As the comet approaches the Sun, and the nucleus becomes active, the spacecraft will maneuver out to a safe distance of 5,000 kilometers or more to observe the formation of the comet's coma and tail. The primary mission will end approximately 150 days after perihelion.

Mission Goals

- Determine the composition and physical state of the cometary nucleus.
- Understand the processes that govern the composition and behavior of cometary atmospheres and their interaction with the solar wind.
- Characterize the development of the coma.
- Characterize the dynamics of, and the processes involved in, the formation of comet tails.
- Determine the composition and mineralogy of the surface of an asteroid.
- Determine the surface morphology and evidence about the internal properties of an asteroid.
- Determine the geodetic character, mass, and density of an asteroid.

Mission Status

- Project in Phase B planning stage.
- Candidate new start project for FY 1988.

Saturn Orbiter/Titan Probe (Cassini)

Mission Description

Cassini is tentatively scheduled for launch in the mid-1990s and will be the first cooperative venture between NASA and ESA on an interplanetary mission. Flight time to Saturn will be seven years, including a swingby of Earth to increase the speed of the spacecraft. An atmospheric probe, carried by the spacecraft, will be launched toward Saturn's largest moon, Titan, ten days before the spacecraft first flies by Titan. Entering Titan's atmosphere, the probe will make extensive atmospheric measurements during its two-hour descent to the surface. Data will be relayed to Earth by the spacecraft. Once the probe mission is complete, the spacecraft will continue in orbit about Saturn. The orbiter will conduct a comprehensive survey of the Saturn system for a period of three years. Its orbit will be varied, so that the entire system of Saturn's rings and moons can be explored, using Titan's gravity field for repeated gravity assists. With each flyby of Titan, radar images of its surface will be made until most of Titan's surface is mapped.

Mission Goals

SATURN ORBITER

- Determine the three-dimensional structure and dynamical behavior of Saturn's rings.
- Determine the surface composition and geologic history of each of Saturn's moons.
- Determine the nature and origin of the dark material on Iapetus' leading hemisphere.
- Measure the three-dimensional structure and dynamical behavior of Saturn's magnetosphere.
- Study the dynamics of Saturn's atmosphere at cloud level.
- Study the time variability of Titan's clouds and hazes.
- Characterize Titan's surface on a regional scale.

TITAN PROBE

- Determine the structure and chemical composition of Titan's atmosphere.
- Determine the exchange and deposition of energy within the atmosphere.
- Locally characterize the surface morphology.

Mission Status

- Preliminary studies on the spacecraft and probe are continuing.

The SSEC also provided specific recommendations for the establishment of the Core Program.

The concept behind the Core Program is the recognition that the existing technical base developed during the last 20 years–launch vehicles, spacecraft, tracking networks, and ground support–is already sufficient to carry out many new missions with extensive and exciting science yields. By using these existing capabilities, by increasing the efficiency with which we build and fly *Voyager*- and *Galileo*-class spacecraft, and by making normal advances in scientific instrumentation, the U.S. can take advantage of its previous investments to maintain leadership in planetary exploration.

The Core Program Missions will typically involve sophisticated remote sensing of other planets and direct measurements with atmospheric entry probes. Such missions require no new enabling technology and no new support facilities. As a result, these missions need not be either expensive or risky.

The financial resources required to support this Core Program are equivalent only to the lowest levels of past planetary program funding, rather than to the intermittently high levels created by large and complex missions like *Viking* and *Voyager*. An effective Core Program can be undertaken through the end of the century at a cost of about $325 million per year (FY 1984 dollars). This effort can include a lean but effective ground-based research program, data analysis from past and ongoing missions, and instrument development. These ground-based efforts rely heavily on universities, as well as on NASA centers, to provide essential talents–both scientific and technical–to the program.

Since the first part of the SSEC Report was published in May, 1983, the *Magellan* mission (previously known as the *Venus Radar Mapper*) was approved by the Congress as a new start mission for FY 1984, the first such new planetary start since *Galileo* in 1977. In FY 1985 the *Mars Observer* (previously known as the *Mars Geoscience/ Climatology Orbiter*) was also approved as a new start. Extensive efforts are also going forward to study and develop future missions in the Core Program, especially the *Mariner Mark II* series, beginning with the *Comet Rendezvous/Asteroid Flyby* (CRAF). In other parts of the program, development of the common Mission Operations and Information System (MOIS), which will support a number of planetary missions, is well under way, as are efforts to improve the funding of areas like Data Analysis and Instrument Development.

The Augmented Program

Despite the value and cost-effectiveness of the Core Program, it has two critical limitations that were recognized and addressed by the SSEC. First, some notable, high-priority science goals cannot be addressed within the scope and capabilities of the Core Program. In particular, such well-established scientific goals as the return of samples from Mars, the exploration of Titan's surface, and the return to Earth of pristine fragments of comets and asteroids for

laboratory study must be excluded from the Core Program on the basis of cost alone.

Second, the Core Program is limited in addressing other important national goals related to the exploration of space. During the last two decades it has been amply demonstrated that the U.S. planetary exploration program, while pursuing science and exploration, has also supported other national aims. Among these are: stimulation of high technology, enhancement of national pride and prestige, and creation of a positive climate for the scientific education of the nation's youth. If the past continues to be any guide, the more ambitious missions needed to achieve scientific goals must also be capable of supporting these other national priorities.

The Core Program, by its definition, is deliberately lacking in technological challenge, and it will not produce all the new capabilities needed for solar system exploration after the year 2000.

For these reasons, the SSEC recommended that the Core Program be augmented at the earliest opportunity by missions of the highest scientific priority that are significantly more challenging technically. These include the autonomous operation of a mobile scientific rover on the surface of Mars, the automated collection and return of samples from that planet, and the return to Earth of samples from asteroids and comets.

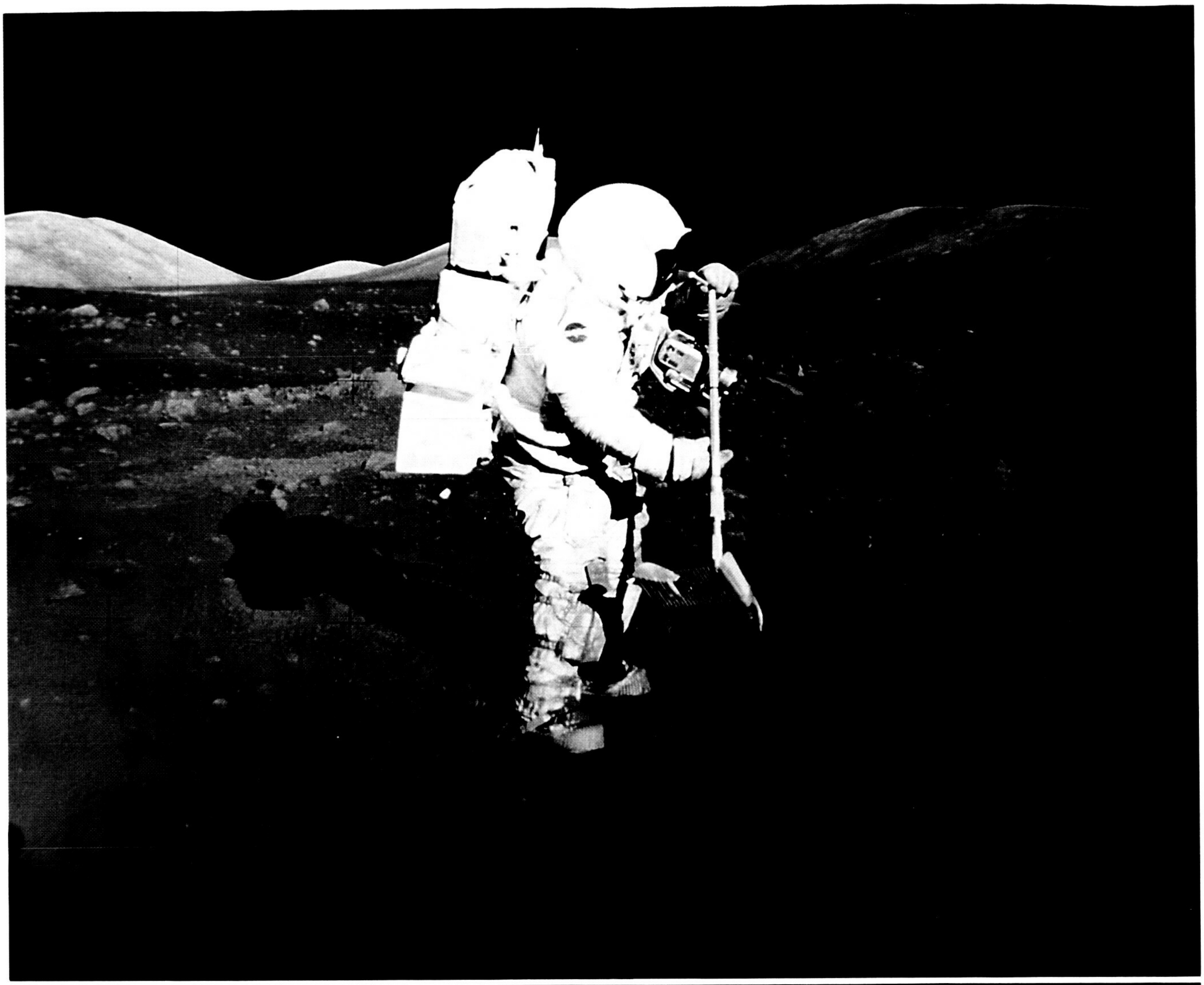
These missions, with their new technical capabilities–especially the ability to return extraterrestrial samples to Earth–will take planetary science to a new high level of understanding of the solar system. Such activities will also provide the same beneficial technological challenges that planetary exploration has provided in the past and will set the stage for the exploration of the solar system well into the next century.

An important by-product of these challenging missions will be the generation of the same intense national and international interest that followed the *Surveyor, Viking,* and *Voyager* spacecraft as they led the way out into the solar system in the 1960s and 1970s. This interest will substantially benefit the nation at home and abroad and will assure that the United States continues to be at the forefront of this epic adventure.

This second report of the SSEC provides detailed recommendations of mission activities suitable for the Augmented Program, including:

- More challenging missions of the highest scientific merit to the inner planets, small bodies, and outer planets of the solar system *(Chapters 2, 3, 4, and 5).*
- Missions and activities needed to lay the groundwork for the eventual utilization of near-Earth resources *(Chapter 6).*
- Potential activities which can, in the near future, lead to the discovery and detailed study of other planetary systems *(Chapter 7).*
- Technological developments that are essential in the near future to make these missions possible *(Chapter 8).*

Apollo 17 *astronaut, Harrison Schmitt, collecting samples with a lunar rake.*



2. The Long Reach

WHY SAMPLE RETURN MISSIONS

The Role of Rocks

Missions designed to collect and return samples of other worlds to Earth are some of the most important candidates for Augmentation Missions to the Core Program. Such missions provide an essential scientific yield–unique information about the composition, history, and evolution of other worlds. At the same time, sample return missions generate exciting technical challenges; they require sophisticated robotic spacecraft systems and the ability to carry out, from Earth, complex operations on the surfaces of distant worlds.

The scientific information contained in returned samples is an essential part of planetary exploration. We cannot understand other worlds without making detailed and careful analyses of the materials of which those worlds are formed. The character of a planet, and the processes that have shaped it, are reflected and preserved in its solid bedrock and surface materials. The shapes and arrangements of crystals in a rock, or in a piece of solid ice from a comet, reflect the original conditions of formation. It is easy to distinguish, for example, between lava flows that cooled quickly on the surface and deep-seated crustal rocks that cooled slowly at depths of tens or hundreds of kilometers.

The different minerals of which a rock is made record further details–its formation temperature, the cooling rate, the nature and abundance of any volatiles present, and the genetic relations between minerals formed at different times. In this way, a single rock can provide the key to recognizing global planetary processes–core formation, crustal separation, episodes of widespread volcanism, and large meteorite impacts.

Of perhaps even more importance is the fact that extraterrestrial rocks, like terrestrial ones, preserve atomic memories of *when* these major planetary events took place. Techniques for measuring the radioactive parent and daughter elements in rocks can be applied with almost unbelievable sensitivity and precision to provide a detailed and independent history of the origin and evolution of a world.

The actual return of extraterrestrial samples (in contrast to the *in situ* analysis of rocks and soil on the surface of another planet) is more than worth the extra effort required, for the scientific yield is virtually unlimited. Returned samples can be analyzed in detail with the complete range of instruments available in the most sophisticated terrestrial laboratories, not just with the few limited instruments that can be carried on a spacecraft.

Furthermore, because the samples have been returned from a *known* location on a *known* world, the large amount of data extracted from them can be added systematically to the planetary information obtained by other methods: field mapping and descriptions (of both the sampling site and the whole planet), imaging, multispectral remote sensing (using both spacecraft and ground-based telescopes), atmospheric analyses, surface geophysical measurements, and theoretical studies. The *Apollo* lunar samples, for example, are not just moon rocks; they are a key element in the large structure of current multidisciplinary information about the Moon.

Even with known sampling locations, more than one sampling site is needed to understand a whole world. We learned from the six *Apollo* and three U.S.S.R. *Luna* sample return missions that even the two fundamental provinces of the Moon–the dark, lava-filled maria and the older, heavily cratered highlands–are strikingly and significantly different from place to place. Mars, a more complex planet, has even more fundamentally different regions: ancient cratered terrains, younger volcanic landforms, erosional valleys, wind-deposited sediments, and polar ice caps.

In planning the systematic study of planets, sample return missions are a special class of *Intensive Study* missions that are ideally

Conversations with a Moon Rock: A World Revealed

The successful collection and return of lunar samples to Earth was one of the greatest achievements of the *Apollo* missions. Studies of the lunar rocks and soil, carried out by hundreds of scientists on Earth, obtained information about the nature and history of the Moon and the solar system that could not have been obtained in any other way.

Some of the discoveries made possible by study of the lunar samples are:

- The Moon has a *unique chemical composition,* totally different from the Sun and from meteorites. In general, the Moon is similar in composition to Earth, but there are important differences. (For instance, the Moon is very low in *volatile* elements like sodium, potassium, and lead.)
- The moon rocks contain *absolutely no water.*
- There is *no evidence of life,* either living or fossil, in the moon rocks. In fact, there are virtually no carbon or organic compounds in the moon rocks.
- The Moon *formed at the same time as Earth,* about 4.6 billion years ago.
- The Moon and Earth have been *separate bodies* ever since they formed.
- The Moon underwent a *major chemical separation* immediately after formation, involving the formation of a crust, a mantle, and possibly a small metallic central core.
- Later on, the Moon became hot enough inside to melt and to produce *great eruptions of molten lava* onto its surface from about 3.9 to 3.3 billion years ago.
- The Moon has been *geologically quiet* for the last 3 billion years, aside from bombardment by large and small meteorites.
- The Moon had a *strong magnetic field* about 3 billion years ago, although it has none today.
- Material from the Sun, trapped in lunar samples, shows some *major changes in composition* during the past 2.5 billion years.
- Past *variations in cosmic-ray activity* are recorded in lunar samples.
- Several *meteorites from the Moon,* virtually identical to lunar samples, have been identified in Antarctica, where they fell on the polar ice cap after being blasted off the Moon by large meteorite impacts.
- Methods to preserve and analyze moon rocks are now being *applied successfully to other extraterrestrial samples:* long-known meteorites, new meteorites discovered on the Antarctic ice cap, and tiny particles of cosmic dust collected from Earth's atmosphere by high-flying aircraft.

ORIGINAL PAGE
COLOR PHOTOGRAPH

undertaken after the global characterization of a world *(Exploration)* has been completed, perhaps even after some *in situ* analyses have been made on its surface. Sample return missions strongly enhance the global data base by providing detailed characterization of the planetary surface and subsurface material at specific locations and by providing essential historical data for understanding planetary evolution.

The scientific value of returned planetary samples is largely independent of whether they are returned by manned missions or by automated spacecraft. In the case of the Moon, the only solar system body sampled so far, both techniques have been used successfully; there were six sample returns by the U.S. manned *Apollo* missions and three by automated U.S.S.R. *Luna* spacecraft. Costs and benefits differ between manned and unmanned missions. Automated spacecraft are less expensive, but their surface operations and the weight and variety of their sample return are limited. Manned missions are more complex and more expensive, but they provide a larger and more diversified sample suite, together with considerable on-site selection and characterization.

Reading the Rocks: What Returned Samples Tell Us

To appreciate the information that returned samples can provide, we need only examine the extensive past studies of extraterrestrial materials that came, or were brought, to Earth: meteorites, lunar samples, and cosmic dust particles. These studies, especially since 1969, have amply demonstrated that analyses of returned samples provide unique and essential planetary data that cannot be obtained by other kinds of space missions.

Independent Ages and Historical Data

Analyses of returned samples provide a critical factor–the time dimension–without which planetary processes cannot be fully understood. Precise measurements of radioactive parent-daughter element pairs can establish a detailed and objective chronology for both planetary and solar system development.

The importance of this chronological information is a major reason for sample return missions. The measurements require large mass spectrometers, complex physical and chemical separations, and a high degree of laboratory cleanliness. It would be virtually impossible to duplicate the procedures, and to obtain the accuracy of terrestrial measurements, with instruments which are scaled to fly on an automated spacecraft.

Three different types of information can be obtained from these age determinations: the times at which specific planetary events occurred, the time limits on processes that went on during the formation of the solar system, and the calibration of a solar-system-wide time scale based on the impact cratering of planetary surfaces.

PLANETARY HISTORY. The timing of specific planetary events (crustal formation, volcanic eruptions, meteorite impacts) involves age-dating techniques which have long been used to study both terrestrial and extraterrestrial rocks. If the rate at which a radioactive parent element transforms (decays) to a daughter element is known, then measuring the amounts of parent and daughter elements makes it possible to determine the time since the rock formed. Measurements of meteorite ages have yielded values of about 4.6 billion years, indicating that the solar system formed at that time. The ages determined on returned lunar samples have provided a rich history of both planetary formation and later events.

FORMATION OF THE SOLAR SYSTEM. A second kind of age-dating attempts to answer the question, "How long did it take the solar system to form?" These measurements try to detect the daughter elements produced from short-lived radioactive parents that were briefly present when the solar system formed, were quickly incorporated into the first-formed meteorites, and then decayed completely with time, leaving only their daughter elements as evidence that they had been there.

Measurements made on both meteorites and ancient lunar rocks suggest that the first solid materials formed in the ancient solar system in only a few million years, and some recent work suggests that this formation interval may have been a million years or less. In addition, these studies indicate that the decay of short-lived radioactive parents could have generated enough heat to explain the evidence (found in both meteorites and lunar rocks) that there was widespread and intense melting when the planets first formed.

A SOLAR SYSTEM TIME SCALE. Finally, age measurements of younger planetary events such as volcanic eruptions may do more than just define the later development of a world. This information may also help develop a uniform time scale for the whole solar system based on the process of impact crater formation on the planets. In theory, the more impact craters on a surface, the older the surface is, and if the meteorite bombardment rate is known, then the age of the surface can be calculated.

In practice, the situation is more complicated–the impact rate varies from place to place within the solar system and has also varied greatly with time. To get around these problems, it is therefore necessary to count the craters on surfaces–such as widespread volcanic lava fields–whose ages can be *independently* measured from returned samples. Then the bombardment rate can be calculated, and the data can be applied to estimate the ages of other, unsampled, planetary surfaces.

The age measurements on lunar samples, combined with counts of craters on the surfaces from which they were collected, have made it possible to estimate–although with considerable uncertainty–the ages of surfaces on worlds as distinct as Mars, Phobos, Callisto, Ganymede, and the moons of Saturn. A major goal of future sample return missions is to obtain independent age measurements from other planetary surfaces, in order to refine the crater-count technique and to apply it even further.

It is not possible to predict in advance what the ages and histories of solid planetary materials will be, and each solar system object generates its own set of historical questions. For an evolved planet like Mars, the questions are much like those originally asked about the Moon: How rapidly was it formed? How old are its oldest preserved rocks? Is there a record of an early intense bombardment? When did its volcanoes erupt, and for how long? How old are the most recent meteorite impact events? How long ago did water flow in the strange and varied channels that cut across the planet's surface?

By contrast, age measurements on a comet (most probably made on cometary silicate dust) aim at questions involving the earliest history of the solar system. Is the comet the same age as the rest of the solar system? Is there older material in it? Is there evidence that short-lived radioactive elements or even pre-solar materials were incorporated into the comet when it formed? Is there any unaltered interstellar material preserved in the comet?

Precise Chemical and Isotopic Data

Accurate measurements of a wide range of chemical elements are essential to characterize a planet, to probe its interior, and to establish its history. The *in situ* analyses of solid surface materials made by automated spacecraft (the *Surveyors* on the Moon and the *Vikings* on Mars) have been limited to a few elements, measured with relatively low precision. By contrast, the current capabilities of terrestrial laboratories, shown by work on meteorites and returned lunar samples, include routine measurement of 60 to 70 elements (whose abundances range from tens of percent to parts per billion).

The implications of these data extend far beyond the sampling site itself.

- Certain chemical characteristics, such as the potassium/uranium ratio, can be used to characterize a world on a global scale and to establish similarities and differences between other worlds.
- Potassium, uranium, and thorium, even though they may be present only in parts per million, can determine the thermal history and the outward heat flow of a planet through the heat generated by their radioactive decay.
- The surface abundances of iron and related elements (nickel, cobalt, platinum, iridium, and gold) provide information about the existence of a planetary core and the time at which it formed.
- The same group of elements (especially nickel, cobalt, iridium, and osmium) also makes it possible to detect the mixture of extraterrestrial material mixed into the planet's surface rocks and soils by impacting meteorites.
- Other elements (the rare-earth metals, rubidium, and caesium) reflect the processes involved in the formation and development of a planetary crust and can be used to determine the nature and history of the crust and its underlying mantle.

Of Time and the Moon: History Preserved

Rocks as Clocks

The search for hidden history is one of the most important reasons for collecting rock samples from a planet or any solid object in the solar system. A rock sample is a geologic clock, recording the key events that shaped its world.

After a rock is formed, tiny constituent amounts of unstable radioactive *parent* atoms (such as uranium, thorium, potassium-40, or rubidium-87) decay, or change, into new *daughter* atoms. The rate at which this change goes on can be measured in the laboratory. Once this rate is known, measuring the amounts of parent and daughter atoms in a terrestrial rock, a lunar sample, or a meteorite, can help unravel the history of the rock: when it formed, when it was heated, even when it was blasted off its original world and exposed to space.

By measuring many different rocks, a geologic history of a world can be established.

History of the Moon

From meteorites, we have learned that the solar system formed about 4.6 billion years ago. From the *Apollo* samples returned from the moon, we have been able to establish the general outline of its history.

Craters, Craters Everywhere

Age measurements for the Moon also play a critical role in determining the histories of even more distant worlds. Because we do not yet have samples from other worlds, a different "clock" is used–the steady bombardment of their surfaces by meteorites to form large and small impact craters. If the bombardment rate is known, then the age of a planetary surface (such as a lava plain on Mars or an icy crust on Callisto) can, in principle, be calculated by simply counting the number of craters on it. The number of craters, divided by the impact rate, should give the length of time since the surface was exposed to the bombardment.

In practice, the situation is much more complicated. The meteorite bombardment rate varies considerably, not only from place to place within the solar system, but also over time. (For example, bombardment rates for the Moon between 3.7 and 4.5 billion years ago were orders of magnitude higher than they have been since.) For these reasons, planetary *crater-count ages* always have a high uncertainty associated with them.

In seeking to improve crater-count ages for other worlds, the data from lunar samples have been invaluable. The ages of several lunar surfaces, which were formed by large volcanic eruptions, are known exactly by dating samples collected from them. We can now determine, for one planetary body at least,

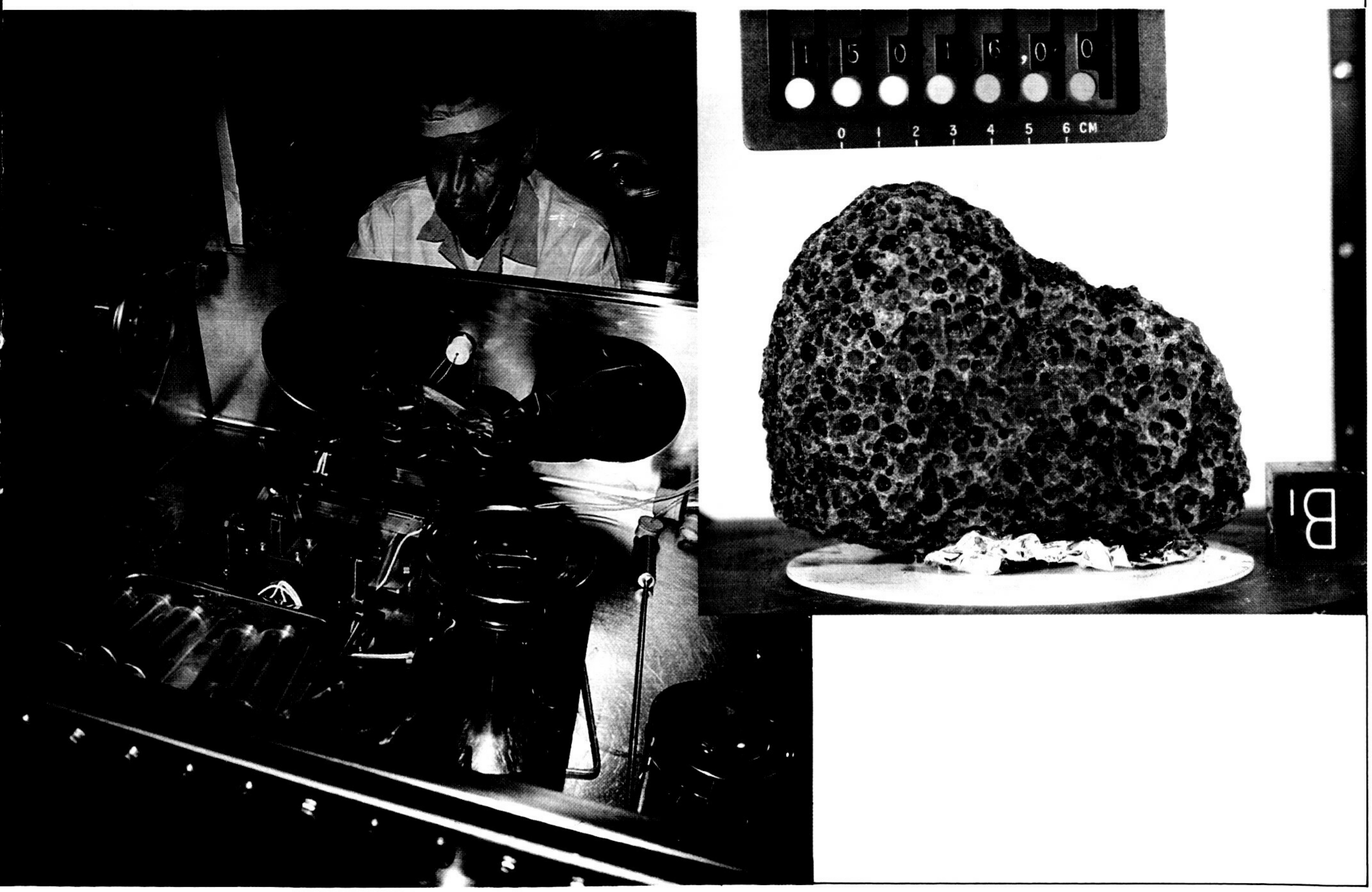
Billions of years ago	Event
4.6	Moon forms, at same time as Earth and solar system.
4.4	Major separation of Moon into chemically distinct regions: outer crust, inner mantle, possibly a small metal core.
4.4-3.9	Intense continuing bombardment of Moon by large objects (ten to 100 kilometers diameter), producing heavily cratered high-lands and large circular basins on both nearside and farside.
3.9	Large impact forms great basin of Mare Imbrium, scatters ejecta over large part of Moon.
3.8-3.3	Huge eruptions of basalt lava from deep within Moon, forming dark-colored filling of older impact basins, mostly on nearside of Moon.
3.3-present	Little geologic activity.
1.0?	Formation of Copernicus impact crater.
0.1?	Formation of Tycho impact crater.

ORIGINAL PAGE
COLOR PHOTOGRAPH

the relations between visible craters on the surface and the exact age of the surface, giving us a good estimate of the bombardment rate since the surface formed. We are now applying the statistics obtained from the Moon to estimate the ages of other planetary surfaces from Mercury outward to the newly seen moons of Uranus.

The number of craters on a planet is also a clue to the amount of geologic activity that goes on. Geologically active planets show few craters, because such processes as volcanism, erosion, and plate tectonics destroy old craters and expose fresh new material to the continuing bombardment. The solar system is full of extremes: Mercury and the Moon are old, geologically inactive, and heavily cratered, while Earth and Venus are highly active and have few visible craters. The large moons of Jupiter provide a full range: the heavily cratered surface of Callisto appears to date from the formation of the solar system 4.6 billion years ago, while the surface of innermost Io, continually renewed by volcanic eruptions, shows almost no impact craters at all.

Analysis of a piece of lunar vesicular basalt at NASA's Planetary Materials Laboratory in Houston.



- Gases (volatiles) trapped in the rocks and soils of a planet provide a wealth of data. The gases come from many sources–internal radioactivity, past and present atmospheres, and the solar wind–and they provide essential insights into the origin of the planet, the global budget of such key species as water and carbon dioxide, and the origin of the rocks themselves.

"Ground Truth" for Global Planetary Missions

Well-characterized samples from selected locations on a planet provide an important calibration for remote-sensing measurements made from orbiting spacecraft or from Earth. This relationship was strongly demonstrated for the Moon by the *Apollo* program, in which returned samples provided geochemical calibrations for the orbital science instruments (X-ray and gamma-ray detectors) that measured the surface composition of the Moon from orbit over about one quarter of its surface. The sample results also support continuing multispectral observations of the Moon that are being carried out with Earth-based telescopes. Other types of "ground truth" provided by returned samples include data on physical properties that are needed to interpret such critical geophysical data as seismic wave records and heat-flow measurements.

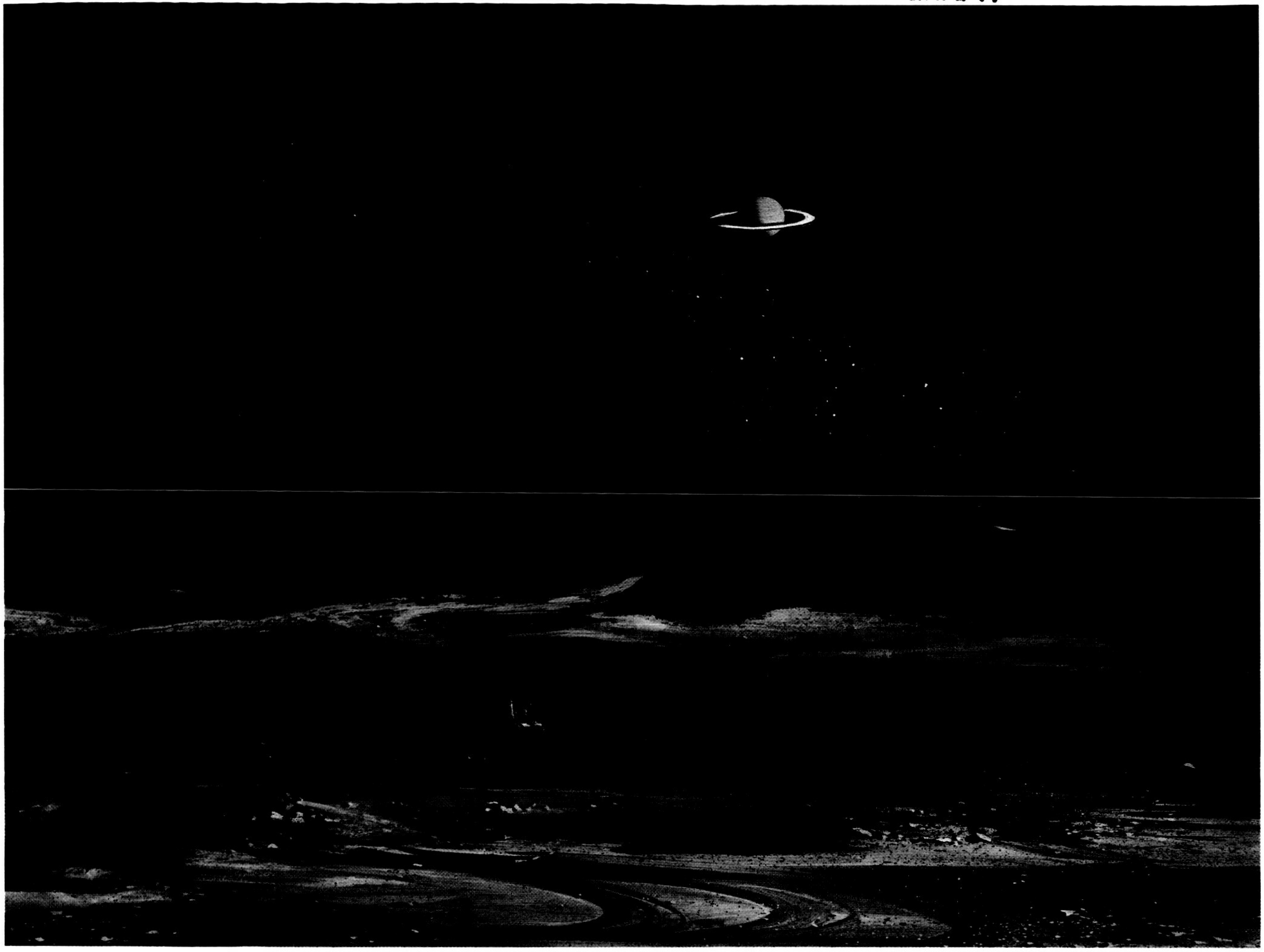
Nature and History of the Space Environment

The surfaces of airless objects like the Moon and asteroids are continually struck by the matter and energy that pass through the solar system. Tiny particles of cosmic dust strike exposed surfaces and produce microcraters. Charged atomic particles from the Sun and from cosmic rays are trapped within the exposed surfaces of surface particles and fragments. Because the surface materials may be exposed for tens or hundreds of millions of years, they trap and preserve a historical record of the cosmic dust flux, the activity of the Sun, and the nature of cosmic rays that come from beyond the solar system.

Counts of microcraters formed on the exposed surfaces of lunar rocks have already provided important data about the rate of bombardment of the Moon by small particles. This information has in turn given us new insights about the dust flux in interplanetary space and about the development of the fragmental surface layers (regoliths) on other airless bodies such as Mercury and the asteroids.

Rocks from other worlds are also important probes into the nature and history of the Sun. Actual atoms from the Sun, sprayed out into space by the solar wind and solar flares, have been trapped in particles of lunar surface materials over long periods of time. In short, by going to the Moon, we have sampled the Sun as well. Lunar samples actually contain a record of solar activity that may extend as far back as 2 billion years. A more ancient record of the Sun is being obtained from certain meteorites, which contain grains that were exposed to the solar wind and solar flares at the beginning of the solar system 4.6 billion years ago.

Automated sample collection in progress on Saturn's peculiar moon, Iapetus.



Analytical Advantages of Returned Samples

Analyses of returned samples in terrestrial laboratories have several advantages over similar analyses performed *in situ* by instruments on a spacecraft.

All Available Instrumentation Can Be Used

Flight instruments on spacecraft are substantially less capable than their ground-based equivalents because of constraints imposed by the spacecraft on size, weight, power, operating time, and data transmission. In a terrestrial laboratory, these limitations do not apply, and studies are limited only by the amount of available samples, the number of interested scientists, and the funds available. One can contrast the gas chromatograph/mass spectrometer (GCMS) instrument flown on the *Viking Landers*, which weighed 25.6 kilograms, with the current state-of-the-art instruments in terrestrial laboratories, which can weigh many hundreds of kilograms and can fill whole rooms. For age measurements, the required mass spectrometers and auxiliary equipment can weigh several tons.

Another powerful advantage of Earth-based studies is that major analytical facilities–nuclear reactors to produce high neutron fluxes, hypervelocity gun ranges for shock-wave and cratering measurements, synchrotrons to produce charged-particle beams and intense X-ray sources–are already available for sample studies.

Analytical Instruments Are Current State of the Art

Terrestrial laboratory instruments can provide the greatest possible sensitivity, resolution (both spatial and spectral), precision, and accuracy. These capabilities are essential if we are to continue to extract the greatest possible amount of information from samples. Even now, existing instruments are being pushed to their limits to analyze such microscopic particles as cosmic dust or the tiny individual components of lunar soils and carbonaceous meteorites.

Furthermore, the instruments used to analyze returned samples will reflect the state of the art *at the time the returned sample arrives on Earth*, not the state of the art existing when the mission design is frozen several years before launch. A sample return mission can therefore benefit from as much as a decade of additional instrument development time. Given the current trends in the direction of increased analytical capability with smaller sample sizes, this additional time can produce a major increase in the amount and quality of science information that the returned samples provide.

Experiment Planning Is Much More Flexible

For missions involving *in situ* analyses, the experiments must be designed rather firmly against an assumed sample material. Assumptions are necessarily conservative and general, so that the flight instruments cannot be optimized for a specific type of material. After landing, if the actual surface material is different from what was assumed, the experiment is neither optimum nor flexible, and it has only limited scope for modification.

By contrast, returned sample studies are virtually independent of the character of the returned sample, because the array of instruments and planned analyses can be continually modified as actual results are obtained. Furthermore, the results of preliminary examinations can be used to eliminate planned analyses that are no longer appropriate, to add new ones that turn out to be needed, and to develop interdisciplinary experiments that yield a maximum of information from a minimum amount of sample. In particular, totally new experiments, not included in the original plans, can be designed and carried out on the basis of early results.

Furthermore, the pressures caused by limited available time on an *in situ* spacecraft mission are absent in returned sample studies. Procedures and measurements can be carefully planned and checked, and the process of iterative experiment planning can continue indefinitely as new results are obtained.

General Advantages of Returned Sample Missions

Characteristic	Sample Returned to Earth Laboratories	Instruments on a Spacecraft
Variety of available techniques	Unlimited	Payload-limited (maximum 6-12)
Currency of technology	Up-to-date	Frozen before launch (5 years or more before analysis made)
Resources available (mass, power, data readout)	Virtually unlimited	Severely limited by spacecraft power, transmission, data rates
Sample processing, sorting, manipulation	Straightforward–human/ mechanical; as complex as needed	Limited to fairly simple operations by mechanical and computer constraints
Ability to make analyses requiring extensive or complicated sample preparation	Generally routine	Generally impossible
Sensitivity and resolution of methods - spatial (particle size, areas) - wavelength (spectral data) - chemical composition - isotopic mass spectra	State of the art	Limited by weight, power, and size constraints on instruments
Capability for replicate, confirming analyses	Easy (depends only on available samples)	Generally not possible
Ability to modify analyses on basis of initial results	Unlimited	None or very limited
Ability to carry out analyses not originally planned	Unlimited	None or very limited
Dependence on previous ideas of what sample characteristics will be	Virtually independent (only in planning, early analysis)	Almost completely dependent
Ability to apply future techniques and procedures	Routine (requires only sample preservation, documentation)	Not possible
Sophistication required for equipment operation, data readout	On-shelf techniques routinely available–human intervention possible at all times	Technically very demanding

Sample Materials Are Available Indefinitely

One of the most valuable by-products of the *Apollo* program has been the development of sophisticated techniques for the long-term preservation of extraterrestrial materials. With these techniques in hand, sample degradation is minimal, even over periods of decades, and returned samples can continue to be a critical resource for future studies. The samples remain available for study by new techniques as they are developed.

The lunar sample collection continues to be an active focus of study and discovery more than a decade after the individual missions took place. As new scientific problems are identified, new studies are undertaken that may include even the samples from the earliest missions. Thus, even the first *Apollo 11* samples are still playing an important role in research aimed at understanding the large variety of lava types that exist on the Moon. The *Apollo 14 breccias*, which are complex fragmental rocks collected from the lunar highlands, continue to be an exciting source of new lunar rock types.

Meteorites have also retained untapped potential for years, even decades, after they were collected. The Allende meteorite, which fell in 1969, is still the focus of active study and will continue to provide critical information about the earliest physical and chemical processes in the solar nebula. Even older meteorites become suddenly and unexpectedly important. A rare group of meteorites (the *shergottites*), some of which fell over a century ago, has suddenly been placed in the spotlight as possible samples from Mars.

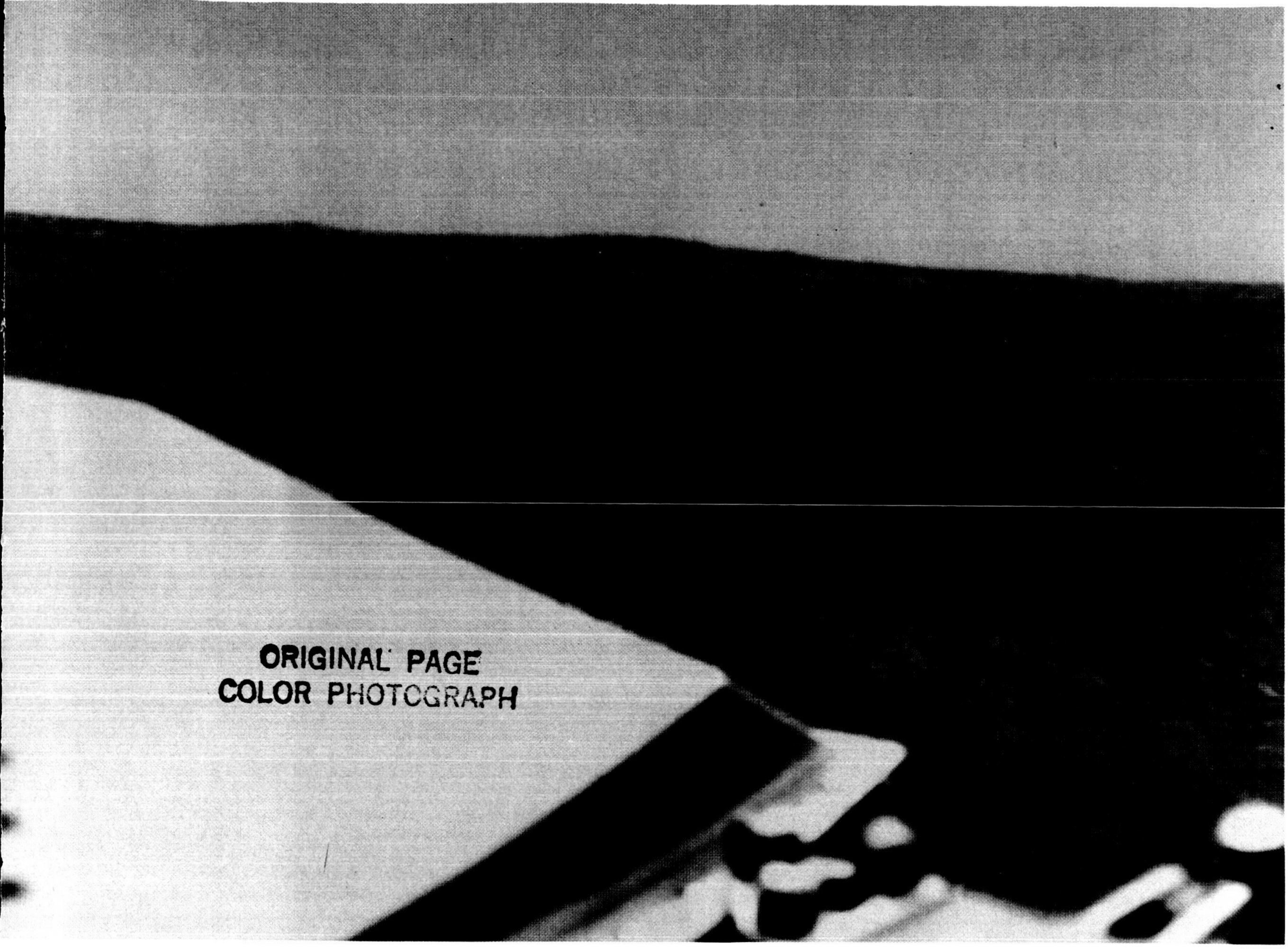
Handling, Processing, and Preservation Are Straightforward

Any spacecraft experiment, no matter how advanced, is severely limited in how it can manipulate and process any sample before and after analysis. These limitations arise from two causes: the mechanical constraints inherent in any practical spacecraft instrument, and the long communication times that may separate the experiment from the scientists back on Earth.

In a terrestrial laboratory, these communication delays are absent. Human beings, highly flexible and adaptable, can interact directly with the sample, subject only to constraints required for sample protection and preservation. As a result, highly elaborate manipulation, processing, and separation activities can be carried out before, during, and after analytical measurements. Furthermore, the system is highly responsive and adaptable; procedures can be changed, and new operations introduced, on the basis of experimental results.

The Planetary Materials Laboratory (formerly the Lunar Sample Curatorial Facility) at the NASA Johnson Space Center (JSC) has been the world pioneer in developing techniques for the preservation, management, documentation, processing, and distribution of extraterrestrial materials. Established originally to manage the collections of returned lunar samples, its expertise and techniques have been successfully applied to two subsequent collections of extraterrestrial samples that were discovered long after the termination of the *Apollo* program–Antarctic meteorites, and the cosmic dust particles collected from Earth's atmosphere. The development of these capabilities, at JSC and more recently in other institutions, demonstrates that future returned samples can be adequately preserved and managed.

Near the **Viking 1 Lander** *on the Chryse Planitia of Mars, a large boulder named "Big Joe" stands a silent vigil.*



Future Sample Return Targets

The worlds of the solar system present an exciting variety of targets for future sample return missions, even if our consideration is restricted only to those objects with solid surfaces. (The return of samples collected from the atmospheres of the gaseous giant planets is not considered here.) The inner planets and the Moon offer relatively dense rocks, made chiefly of silicates. Asteroids probably consist of silicate rocks with varying amounts of metal. Comets may be composed chiefly of volatile ices with an unknown amount of rocks and fine silicate dust. The outer planets and their satellites offer more varied and more exotic materials: silicate rocks, ices, volatiles such as the possible sulfurous deposits of Io or the possible liquid nitrogen seas of Titan, and organic materials.

The targets of most immediate interest for sample return missions in the SSEC's Augmented Program should meet several criteria:

1. They can be reached, and samples returned from them, with technology that can be made available in the relatively near future.

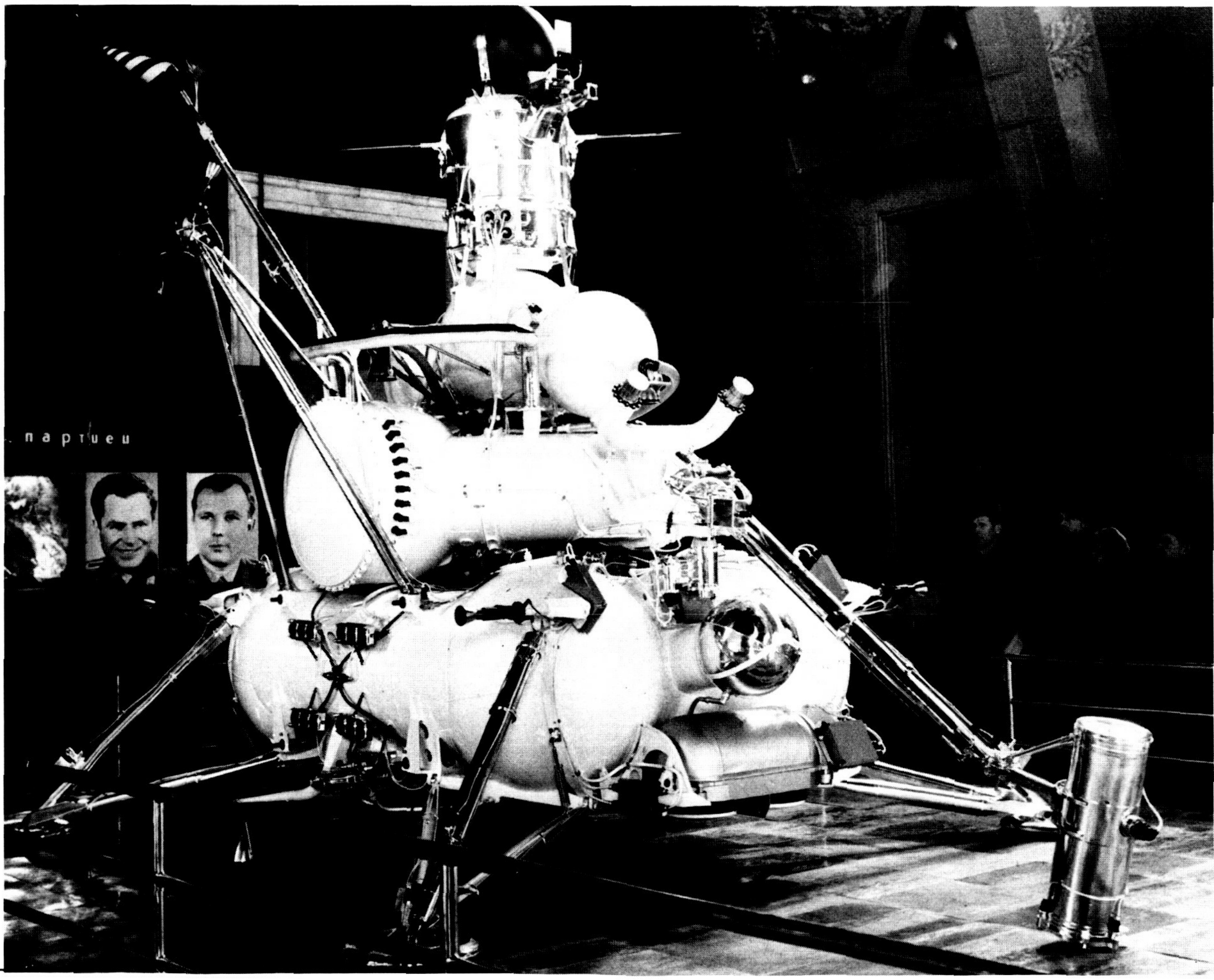
Robot Sample Collectors on the Moon: The U.S.S.R. *Luna 16* Mission

With the *Luna 16* mission, launched on September 12, 1970, the U.S.S.R. demonstrated that a sample of the lunar surface could be successfully collected and returned to Earth by an unmanned, automated spacecraft. In comparison with the stunning achievements of the U.S. *Apollo 11* mission 14 months earlier (which included the return to Earth of 21.7 kilograms of lunar rock and soil), the *Luna 16* mission went almost unnoticed. Taken on its own merits, however, *Luna 16* was a remarkable success and an important harbinger for future planetary exploration.

After a five-day trip from Earth, *Luna 16* entered a low circular orbit about the Moon at an altitude of 110 kilometers and 70-degree inclination. During the next two days, two maneuvers altered the orbit to 15 by 106 kilometers and 60-degree inclination. On September 20, the retro engine fired to begin the final descent. Six minutes later, *Luna 16* landed safely, in darkness, on Mare Fecunditatis (the Sea of Fertility) at 0°41'S and 56°18'E, as planned.

Less than an hour after landing, commands from Earth caused a sampling drill to swing out and begin to penetrate the lunar surface. Seven minutes

Replica of the U.S.S.R. **Luna 16** *robot sample return vehicle.*



later, at a depth of about 35 centimeters, drilling ceased. The scientists back on Earth were not certain whether the drill had encountered bedrock or a hard stone. Nevertheless, rather than risk damage to the mechanism, the drilling was stopped. The sampler was raised, the drill head was rotated 180 degrees, and the drill bit with the lunar soil sample was inserted into the return capsule. The drill head was then pulled back, and an automatic device sealed the bit and sample within the capsule. After some 26 hours on the lunar surface, *Luna 16* blasted off for its return to Earth. Three days later, on September 24, the return capsule separated, entered Earth's atmosphere, and landed safely 80 kilometers southeast of Dzhezkazgan in the U.S.S.R. with its 101-gram cargo of lunar soil.

The *Luna 16* spacecraft consisted of three separate vehicles: a descent stage, an ascent stage, and the return capsule. Each of the two stages contained a full complement of engineering subsystems. Control of the stages was maintained by both preprogrammed information and instructions transmitted from Earth. Power for all three vehicles was supplied only by chemical storage batteries. The descent stage provided guidance and all propulsive maneuvers, made the required soft landing on the lunar surface, collected the sample, and served as the launch platform for the ascent stage. Descent to the surface was controlled with a radioaltimeter, which provided both rate of descent and altitude data. Terminal braking was controlled first by the variable-thrust main engine and four vernier engines. At an altitude of 20 meters, two low-thrust engines took over to minimize exhaust contamination of the landing site.

The ascent stage provided guidance and propulsive maneuvers from lunar liftoff through separation of the return capsule. After departure of the upper stage and capsule, the lower stage continued to transmit data on local temperature and radiation conditions. Trans-Earth injection from lunar orbit was so accurate that no midcourse correction maneuver was required.

The return capsule was a sphere 50 centimeters in diameter, covered with ablation material. Pyrotechnically released metal straps were used to attach the capsule atop the ascent stage. Besides the sealed sample canister, the capsule housed both drogue and main parachutes, a beacon transmitter with whip antennas, a battery, and two long, slender balloons. The balloons were inflated before landing to ensure that the capsule landed in an upright position.

The *Luna 16* sampling mechanism consisted of a rotating arm attached to the descent stage and the drilling unit. The arm was latched up to the ascent stage until after landing, and it was then able to extend out beyond the immediate blast area of the braking rockets. Two telephotometers on the descent stage enabled U.S.S.R. scientists to select the most interesting-looking sampling site within arm motion limits and to visually monitor the operation of the sampling drill. The drill head consisted of a hollow-core rotating drill with sensors to measure the soil's resistance to the drill. The drill's rotation speed was remotely varied in relation to the apparent hardness of the lunar material to prevent overheating.

Two other lunar sample return missions were successfully accomplished by the U.S.S.R.: *Luna 20* in February, 1972, and *Luna 24* in August, 1976. *Luna 20* used a sampling mechanism similar to the one used on *Luna 16*. It landed in a region of the lunar highlands between Mare Crisium (the Sea of Crises) and Mare Fecunditatis and returned a 50-gram sample from a depth of about 33 centimeters. *Luna 24*, however, carried a new drilling rig, designed to obtain samples from a depth of 2.5 meters. It landed in Mare Crisium and returned a 170-gram core sample that provided an important stratigraphic section from the lunar surface to a depth of about two meters.

2. Their surfaces are hospitable enough so that the collecting devices and their associated systems can land, survive, and function on them.

3. They are well enough understood so that a complex sample return mission can be planned. Not only must there be solid material there to sample, but the surface and atmospheric characteristics must be well enough known to design the spacecraft, to develop the sample collection equipment, and to plan the necessary mission operations in detail.

4. Their scientific study has already been far enough advanced by precursor missions so that the contributions of a sample return mission can be defined in detail and a series of candidate sampling sites can be identified.

Evaluating these criteria in the light of our current state of knowledge about the solar system, the SSEC considers that there are two definite targets for sample return missions before the end of the century: the planet Mars and a comet.

Mars

Mars is at present the best-known and most hospitable of the inner planets. From earlier *Exploration* phase missions (*Mariner 9* and *Viking*), we understand the general character of its atmosphere and surface well enough to plan further landings of spacecraft equipped to gather and return samples. Much of the information that a sample return mission could provide about Mars–its chemistry, age, history, evolution, and atmosphere/rock interactions—is relatively independent of the exact site selected for sampling. Important bioscience goals could also be attained through a sample return. The presence of indigenous life–especially fossil life–and the puzzling absence of organic matter in the martian soil, could be investigated directly by the laboratory examination of an unsterilized sample returned to Earth.

Comets

Expanded exploration of the small, primitive bodies of the solar system–comets and asteroids–is one of the highest-priority activities identified by COMPLEX. These targets are a new and virtually unstudied class of objects which, because of their primitive nature, are fundamentally important to understanding the origin and earliest history of the solar system.

Comets may be the only samples of truly primordial material remaining in the solar system. Studies of meteorites have established that even the small asteroid parent bodies (from which meteorites are almost certainly derived) have suffered some types of geologic processing; these meteorites show the effects of metamorphism, melting, and even hydrothermal alteration that have occurred since their parent bodies were formed. Larger objects, such as Earth, the Moon, and Mars, have been even more thoroughly modified from their original state by such global factors as the development of a distinct planetary crust, major volcanic eruptions, formation of an

atmosphere, erosion by water, and the activities of life.

Comets are unique among solar system objects because they have spent virtually all their lives in the low-temperature regions of the outer solar system. Comets therefore probably represent the best-preserved and least-modified samples of original solar system material now available anywhere in the solar system. The acquisition of a returned sample from a comet nucleus would provide a great leap in our continuing attempt to learn about the nature of the early solar system material and the processes that affected it. A returned sample of a comet nucleus would make possible a detailed characterization of the comet's chemistry, mineral composition, physical properties, and age. It would be possible to search such a sample for pre-solar isotopic anomalies or other evidence of interstellar matter in comets. A complete characterization of cometary organic chemicals would be possible, with exciting implications for understanding the origin of life in the solar system. Finally, data from a returned sample would allow direct comparisons of cometary material with other solar system materials (meteorites, asteroids) and with interstellar dust.

Our present knowledge of comets is limited mainly to telescope observations, but the data base will expand drastically as flyby missions in the next few years accomplish the *Reconnaissance* phase of cometary exploration. This phase has already begun. Comet Giacobini-Zinner was encountered by the *International Cometary Explorer (ICE)* in September, 1985. In early 1986, Comet Halley was the target of flyby missions by several spacecraft: the European Space Agency's *Giotto* mission, the U.S.S.R.'s *VEGA* spacecraft, and Japan's *Planet-A* and *MS-T5*. In the 1990s. a planned *Mariner Mark II* mission, the *Comet Rendezvous/Asteroid Flyby (CRAF)*, will provide the much more detailed and extensive data that can only be obtained from a long-duration rendezvous with the nucleus itself. This first complete characterization of a cometary nucleus will provide much of the information needed to make the landing on the nucleus and to collect a sample.

Data obtained from both the flyby and rendezvous missions will be needed to plan and execute a sample return mission. In addition, advances in technology are needed to provide the necessary propulsion capability and to preserve the probably icy sample of the comet under refrigeration on the return to Earth. These challenges, discussed in later chapters of this report, can clearly be met. Once developed, the small-body sample-return technology can be applied to a large number of highly diverse objects–both comets and asteroids.

Other Objects

Other bodies in the solar system (Mercury, Venus, the asteroids, and the moons of the outer planets) are also obvious targets for sample return missions in due course. However, given the excessive technical demands involved in undertaking sample return missions to these bodies, it seems likely that we will be limited to *in situ* missions on these bodies for some time to come.

Sample collection on the surface of Venus during a joint U.S./U.S.S.R. sample return mission.

Summary

Our previous experience, beginning with the intensive study of terrestrial rocks and continuing into the era of the *Apollo* program and modern meteorite research, has established that the analysis of returned planetary samples in terrestrial laboratories is an essential step to adequately characterize the planets. **The SSEC endorses the view of COMPLEX that sample return missions, and the unique understanding of other worlds that they provide, should be an eventual goal of all planetary explorations.**

Our past studies of planetary samples have also created a wealth of capabilities, experience, and confidence that is an essential resource for planning such missions. Together with the U.S.S.R., we have demonstrated that we can obtain samples from other worlds, using both manned and automated missions. We can use the techniques and insights developed and tested on terrestrial

rocks to obtain from planetary samples the same data about their composition, origin, and history. We have successfully developed techniques to protect, preserve, manage, process, document, and distribute samples. And we have learned that sample return missions provide the basis of long-term research efforts that continue to produce a great deal of new and exciting data.

For these reasons, **the SSEC considers that sample return missions represent the highest priority for Augmentation Missions to the Core Program. The SSEC further considers that the most definite targets for sample return missions before the end of the century are the planet Mars and a comet.** Both of these missions combine the grandeur of major scientific discoveries with far-reaching technical challenges. Our available data and our foreseeable technical capabilities are adequate to plan and carry them out. The determining questions are those of timing and available resources. The samples are waiting on other worlds–we need only to resolve to go and get them.

CONCLUSIONS

1. The SSEC endorses the view of COMPLEX that sample return missions, because of the unique and otherwise unobtainable scientific information that they provide about other worlds, should be the eventual goal of all planetary exploration.

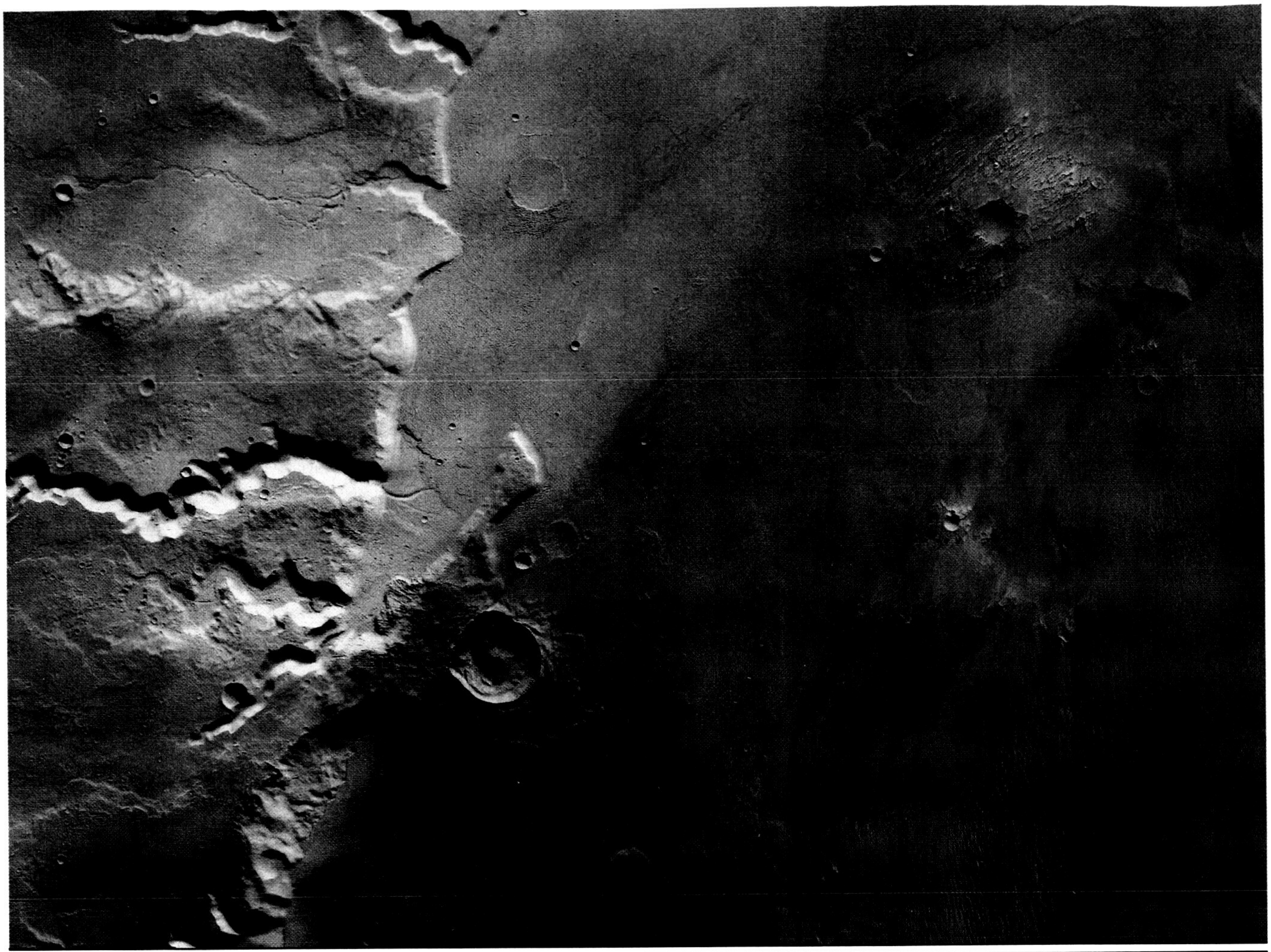
2. Sample return missions, because they combine unique and high-priority scientific yields with major and exciting technical challenges, are the highest priority undertakings for Augmentation Missions to the Core Program.

3. Given the current state of our knowledge about the solar system, together with our current and foreseeable mission capabilities, the two most attractive targets for immediate sample return missions are the planet Mars and a comet.

RECOMMENDATION

As the highest priority for candidate Augmentation Missions to the Core Program, sample return missions to Mars and to a comet should be implemented as soon as possible so that they can be undertaken before the end of the century.

Proposed landing site for a sample return mission–the East Mangala region of Mars.



3. A Handful of Mars

A SAMPLE RETURN MISSION TO THE RED PLANET

The Reasons for Mars

Of all the nine planets and their dozens of moons, Mars still stands out as the one other potentially habitable body in the solar system. Venus has been eliminated from consideration by our space explorations, even though Earth, Venus, and Mars are generally thought of as a similar group of small, rocky, inner planets. In many ways, Venus is a twin of Earth–in size and general composition–but its evolution has produced the very opposite of Earth's surface environment: oven-like temperatures, crushing atmospheric pressures, and a thick corrosive smog which envelops the entire planet. These conditions have slowed our investigation of Venus, and there is little

likelihood that astronauts will ever explore its surface. In short, from our present perspective, the only other planet in the solar system that we can hope one day to understand as well as our own, and perhaps live on as on our own, is Mars.

NASA's current strategy for exploring the solar system is based on the desirability of proceeding in a balanced way to investigate simultaneously the various types of objects in the solar system: the inner planets, the outer planets, and the small bodies. This strategy has served us well so far, and it should continue to guide us. Nevertheless, the special character of Mars has drawn us to explore it to a greater degree than other bodies, and this trend will continue. Three of the SSEC Core Program Missions are directed toward Mars: the *Mars Geoscience/Climatology Orbiter* (now called the *Mars Observer*), the *Mars Aeronomy Orbiter* (now called the *Mars Aeronomy Observer*), and the *Mars Surface Probe* (now called the *Mars Network Observer)* (for details, see Part I of the SSEC Report). **The SSEC also recommends that one thrust of an Augmented Program be Mars-oriented.**

As a result of the highly visible and successful *Viking* missions in the late 1970s, the general nature of Mars has become familiar to most people. The Red Planet is intermediate in size between Earth and our Moon. Part of its surface resembles the Moon and shows massive impact basins, cratered highland regions, and extensive flooding by lavas. Much more exciting are the regions that resemble Earth: mountains, volcanoes, dried-up riverbeds, desert sand dunes, an atmosphere, variable cloud patterns, and seasonal polar caps. Obviously, Mars has evolved to an advanced stage, approaching the development level of Earth. It is even possible that Mars' internal heat engine, powered by the decay of radioactive elements, is still active, producing yet-undiscovered present volcanic activity and exhaling internal gases into the atmosphere.

The fact that Mars has a measurable atmosphere (mostly carbon dioxide with small amounts of nitrogen, argon, and water vapor) and a planetary surface whose temperature may locally rise above the freezing point of water, inevitably raises the question of whether Mars could have developed indigenous life, and a controversy about life on Mars has boiled and simmered ever since the serious study of the planet began more than a century ago. In 1972, the *Mariner 9* images provided evidence that the martian surface had been extensively eroded by huge floods of water. This discovery suggested that Mars might have been even warmer–and its atmosphere thicker–in the past. Under those gentler conditions, could life have developed and survived?

Four years later, two *Viking Landers,* thousands of kilometers apart, sought the answer to this question directly by collecting and analyzing the martian soil itself. The results of these *Viking* biology experiments, in which the soil samples were treated with various nutrients, were either negative or ambiguous. No evidence was found for the presence of martian life. Even more discouraging, a clear answer was obtained about how much organic material (of either biological or nonbiological origin) is present in the surface material of Mars–virtually none. Gas chromatograph/mass

Rocks from Mars: To Understand a Planet

The space explorations of the last 20 years have taken Mars out of the realm of scientific and fictional speculation and have provided a clear picture of a fascinating, puzzling world. Parts of Mars are like the Moon, heavily cratered and probably preserving the earliest records of how the planet formed. Other parts are surprisingly Earthlike. There are none of the artificial canals reported by Percival Lowell, but the orbital pictures taken by the *Mariner 9* and *Viking* spacecraft show volcanoes, canyons, sand dunes, clouds, frost, and strange winding channels that are now as actively debated as were Lowell's earlier canals.

In the post-*Viking* era, the driving need for future exploration of Mars is to understand the details of its character and to decipher its history. Sample return missions will be essential to determine many of the critical details of this neighbor world.

With the experience accumulated by studying meteorites and lunar samples, we can:

- Determine, precisely and in detail, the *chemistry, mineral composition, and physical properties* of fresh martian bedrock.
- Establish quantitatively the *diversity of martian bedrock* types, using the data to trace the geochemical evolution of the planet.
- Use the chemical information to establish definite models for the *internal structure* of Mars: the nature and thickness of its crust, the character of the underlying mantle, and the presence (or absence) of a metal core.
- Determine the nature of the *past magnetic fields* of Mars and whether they were strong or weak.
- Establish an exact *geologic history of Mars*—the timing of crustal formation, major volcanic eruptions, meteorite impacts, and the formation of channels on the martian surface.
- Determine the detailed chemical and physical alteration ("*weathering*") *of martian surface material* through atmosphere/rock interactions.
- Establish the nature and amount of *volatile materials* (water, ices, carbon dioxide) trapped in martian bedrock and surface materials and thus obtain essential data for establishing the reservoirs and cycles of these materials on Mars.
- Determine the chemical and mineral composition of *airborne dust*.
- Examine martian materials thoroughly for *evidence of life* (either living, dead, or fossil) and for organic chemicals.

spectrometer measurements established that there was no organic material above the parts-per-billion level, the sensitivity limit of the instrument.

This result was a major surprise; even in the absence of life, the impact of carbonaceous meteorites on Mars over the aeons should have supplied a substantial amount of nonbiological organic molecules to the surface material. The absence of any organic materials apparently results from the intense ultraviolet radiation that reaches the surface through the largely ozone-free atmosphere of Mars. Such radiation destroys organic molecules both directly and indirectly, through the production of free radicals such as hydroxyl.

The *Viking* results make it hard to sustain the notion that present-day life exists on Mars, even though the basic ingredients (water, carbon compounds, and energy) are all there. Life may have developed on Mars in the distant past, when liquid water may have periodically flooded the surface and when precipitation almost

certainly took place, but this separate issue will probably not be settled until samples of martian rocks can be studied in detail. (The recognition of fossils in rocks such as the layered sedimentary units seen in both the equatorial and polar regions of Mars would be a discovery for the ages!)

Whether or not Mars has ever been an oasis for life, the nature of the planet–and its direct relevance to understanding Earth and other planets–makes it a compelling target for in-depth exploration. A range of geologic processes has operated on Mars to produce landscapes that are alien and yet familiar: individual shield volcanoes that would stretch from Boston to Washington, DC; a canyon that would extend from New York to Los Angeles; and seas of sand dunes that girdle the entire north polar region. Mars is thus a perfect natural laboratory for studying the various geologic forces that shape a planet.

Mars is also a perfect laboratory to investigate planetary weather and climate. The diurnal and seasonal cycles on Mars are remarkably similar to those of Earth, but the extremely thin atmosphere, the rapid heating and cooling of the surface, the lack of oceans, and the enormous vertical scale of the landscape also create critical differences. The condensation cycle of atmospheric carbon dioxide and the exaggerated role of dust in heating the martian atmosphere are also fascinating contrasts to Earth. Despite these differences, we have already learned that martian meteorology is exciting, complicated, and capable of being understood, and a better understanding of the weather of Mars will teach us much about the weather of our own world.

Martian climatology, which is in essence the long-term history of the planet's weather, is a science still in its infancy, but it holds great promise to illuminate not only the history of Mars but also that of Earth. There is ample evidence of massive climate changes on both planets–ice ages, changing seashore-lines, and species extinctions on Earth; regional flooding, glaciation, and periodic polar sedimentary layering on Mars. Common mechanisms could have been at work on both planets–solar luminosity changes, periodic orbital variations, episodes of volcanic eruption, and asteroidal impacts. With detailed comparative data from both Mars and Earth, we can make important progress toward understanding matters of both intellectual and practical importance.

The critical importance of investigating Mars has increased steadily since 1978, when the Committee on Planetary and Lunar Exploration (COMPLEX) of the National Academy of Sciences' Space Science Board declared in its report, *Strategy for Exploration of the Inner Planets, 1978-1987:*

> *"The study of Mars is an essential basic for our understanding of the evolution of the Earth and the inner solar system...* ***we recommend that intensive study of Mars be achieved within the period 1977-1987."***

The three Mars-oriented Core Program Missions, combined with the *Rover/Sample Return* mission to be described in this chapter as

"Canals" to "Channels": The Continuing Mystery of Water and Climate on Mars

Of all the other landscapes seen so far in the solar system, only that of Mars shows evidence that liquid water once flowed across its surface, though not in the canals of a dying civilization as proposed by Percival Lowell. Thus the long scientific debate about the existence of artificial "canals" on Mars was strikingly settled, and then recreated in a new and unexpected form, when the *Mariner 9* and *Viking* spacecraft revealed a network of winding channels, of many shapes and sizes, cutting across the surface of the Red Planet.

Even before the space age, many scientists felt that Mars might have reservoirs of water somewhere on or just beneath its surface. In fact, it was the inferred presence of water that motivated the search for martian life that began with Percival Lowell before 1900 and culminated in the *Viking Lander* missions in 1976. Analyses of the martian atmosphere show a very low water vapor content, but liquid water is not stable on the martian surface under the conditions we see today. However, the channels revealed in such detail by the cameras of the *Viking Orbiters* indicate that water erosion had been a major force in altering the martian surface at some time in the past.

The erosion channels, now studied in detail on the images of Mars provided by the *Viking Orbiters*, come in three basic types: small, medium, and large. The large channels are as much as 1,000 kilometers long and 100 kilometers wide in some places, and the processes which created them are not clear. They may have formed by a catastrophically sudden melting of buried ice or the sudden outflow of water from buried aquifers. Because there is no evidence of seas or lakes on the martian surface, several questions arise. Where did the water go at the end of its journey? Did it just evaporate into the atmosphere, or did it somehow soak back into the subsurface?

The intermediate-sized channels are more numerous; they have a general sinuous shape with many blunt-ended tributaries which may have been formed by water flowing out from the base of cliffs. There are too many tributaries to be explained by local heating alone; some scientists have suggested that they formed during a warmer period in the past as part of a major change in martian climate.

The smaller channels are even more numerous, and early studies have suggested that they could only have formed as the result of rainfall. The nature of the hydrologic cycle is uncertain; the water source may have been underground springs or layers of snow precipitated onto the surface. In the latter case, as the snow melted, the water could have soaked into the ground, forming springs that cut the channels.

Where is all the water now? Like most matters concerning the channels, this question is also a matter for speculation. Some has been observed to be permanently stored in the polar caps as water ice. The remainder may be adsorbed in the martian surface materials or stored in subsurface rocks as hydrous minerals or as permafrost. Study of samples of martian surface material will shed light on how much water exists and how it is bound in these materials.

The presence of water-cut channels on Mars indicates that past climates on Mars were very different from the conditions today. In the past, Mars must have been warmer, its atmosphere must have been denser, and bodies of liquid water could form and flow across its surface. Scientists have attempted to determine the times when the channels formed by counting the craters on their surfaces; the more craters, the older the channel. These measurements show that the channels have a wide range of ages, but all of them are relatively old. The larger channels may have formed during a long interval of time about 2 or 3 billion years ago, while some of the smaller channels may be only a few hundred million years old. Clearly, in collecting samples from these channels, we will be exploring ancient climates.

Clues to more recent climates on Mars, which could be compared with the record of recent climate changes on Earth, may be found in the polar regions, which seem to be relatively young. The layered terrain that surrounds the martian polar caps has few craters, indicating ages of, at most, a few million years, comparable in time to the period of recent Ice Ages on Earth. Samples of this material may reveal the existence of glacial and interglacial periods similar to those recognized on Earth. Measuring the ages of these events from returned samples would make possible the first correlation of Ice Ages between two different planets and would be a major contribution to understanding how such events are caused.

Valleys on Mars. Maja Vallis (at right) and Vedra Vallis (at left) are deeply incised into the old, cratered terrain between Lunae Planum (bottom) and Chryse Planitia (top). North is approximately to the left.

a candidate for the Augmented Program, will address all of the science issues discussed above. In addition, the *Rover/Sample Return* mission (hereafter called simply the *Mars Sample Return* mission) will carry our planetary exploration capability to a new level, by ushering in a period of open-ended unmanned Mars exploration. It will also set the stage for manned exploration of Mars early in the next century, when available technology should make such an undertaking relatively straightforward. **Because of its high scientific importance, and because of its pivotal role in the future exploration of Mars, the SSEC recommends that a *Mars Sample Return* mission be undertaken as soon as possible as one of the first Augmentation Missions in its program of planetary exploration.**

Science Objectives for Mars Exploration

Two precepts, enunciated in the 1978 COMPLEX report quoted above, have guided the formulation of science objectives for Mars exploration. One is the need to achieve a broad-based and balanced planetary characterization in order to draw meaningful comparisons between Mars and the other members of the Earth-Venus-Mars group. The other is the need to carry out intensive studies of the chemical composition, isotopic composition, and physical properties of martian materials.

These precepts, when reconsidered in the light of our current knowledge of Mars, lead directly to several high-priority scientific objectives for the future exploration of Mars:

- Characterize the internal structure, dynamics, and physical state of the planet.
- Characterize the chemical composition, mineral composition, and physical character of surface materials over the planet.
- Determine the chemical composition, mineral composition, and absolute ages of rocks and soil for the principal geologic provinces.

Life on Mars: Definitely Maybe Not?

For both scientists and science-fiction writers, Mars has long been considered as a likely abode for life beyond Earth. About 1900, astronomer Percival Lowell argued that the vague "canals" seen on Mars by some observers had been constructed by intelligent inhabitants to draw irrigation water from the melting polar caps to the dry equatorial regions. Many scientists disputed these ideas, but Lowell's extensive and popular writings generated an intense public interest that has never waned. In fact, it is probably fair to credit Lowell with being (perhaps unintentionally) one of the founders of what has become the formal scientific discipline of *exobiology,* the study of the possible existence and nature of extraterrestrial life.

Three-quarters of a century after Lowell, the possibility of life on Mars was one of the main driving forces that sent the *Viking* missions to Mars to give Lowell's original ideas an on-the-spot test. The two spacecraft that landed on the martian surface carried complete chemical laboratories, compact and sophisticated, designed to determine whether there is (or ever was) life on Mars.

Mars, however, turned out to be more complicated than expected. After completing a detailed set of experiments on the martian surface, the *Viking* biology team was forced to conclude that, "the *Viking* results do not permit any final conclusion about the presence of life on Mars."

The *Viking Landers* contained four experiments that could recognize biological activity or detect the presence of organic (carbon-based) compounds which are the building blocks for all forms of known life. The first experiment, the *pyrolitic gas chromatograph/mass spectrometer,* was designed to detect organic compounds by heating a soil sample in steps to above 500°C. The results were totally negative; organic material was totally absent. This result was completely unexpected; even if no life was present on Mars, the steady bombardment of the martian surface by carbon-bearing meteorites should have introduced organic materials into the martian soil. The complete absence of organic compounds suggested that there was actually some process on the martian surface that *destroyed* organic material, and the martian surface suddenly seemed a far less hospitable place for life than had been thought.

The *Viking* biology experiments attempted to detect life (or at least, biological activity) with three separate experiments. The first attempt, called the *pyrolitic release experiment,* was a physiological test based on the assumption that martian life, like terrestrial life, would assimilate carbon monoxide and carbon dioxide and reduce it to organic carbon. The results of the experiment were "weakly positive," but the experiment could be run only once, and no firm conclusions could be drawn.

The second experiment, called the *labeled release experiment,* used radioactive carbon-14 in an organic nutrient. It was hoped that any martian microbes in

- Determine the chemical composition, distribution, and transport of volatile compounds (e.g., water, carbon dioxide), in order to understand the formation and chemical evolution of the atmosphere and the interaction of the atmosphere with the surface material (regolith).
- Determine the quantity of polar ice, and estimate the quantity of permafrost present on Mars.
- Determine the processes that have produced the landforms on the planet.
- Characterize the dynamics of the martian atmosphere on a global scale.
- Characterize the planetary magnetic field and its interactions with the upper atmosphere, incoming solar radiation, and the solar wind.
- Determine what organic, chemical, and biological evolution has occurred on Mars and explain how the history of the planet constrains these evolutionary processes.

the martian soil would feed on this nutrient and release radioactive carbon dioxide that could be detected. Again, the results were ambiguous. Carbon dioxide was indeed detected, but the process stopped abruptly before the nutrient was used up. If microbes had existed in the soil, carbon dioxide should have continued to be produced until the nutrient was completely used up. The observed results were not conclusive; the data could be explained by either an inorganic chemical reaction or the presence of a unique type of biological life-form.

Finally, the *gas exchange experiment* mixed an inorganic nutrient "soup" with the martian soil samples in an attempt to detect any gases released by biological metabolism. Because the martian soil sample was collected from an initially dry environment, it was slowly humidified so that mixing it with the soup would not "shock" any microorganisms present. However, when the soil was humidified, a sudden release of oxygen was detected. When the soil was then mixed with the "soup," no reaction took place. The experimenters concluded that the soil contained some inorganic oxidizing agent but no detectable life-forms.

These inconclusive results were disappointing to people who had hoped for a definite answer. However, the question of life on Mars remains open. For reasons of safety, the *Viking Landers* landed in flat, accessible regions that may not have been the best places to search for life. Because much of the water on Mars is located near the poles, these areas might prove to be more promising locations, assuming that water is as important to any martian life as it is to terrestrial life-forms. Another problem is that, because of limitations in weight and power, the *Viking* experiments were designed to detect only the kinds of life with which we are familiar. Martian life could be so different that it would escape detection by experiments designed from the viewpoint of terrestrial experience. Finally, the question of the existence of *past* life on Mars (i.e., fossils in the rocks) remains unanswered.

Sample return missions offer unique and definite advantages for investigating further the question of past and present life on Mars. Samples obtained from various geologic areas could be studied and experimented with back on Earth. In clean, contamination-free terrestrial laboratories, samples could be analyzed with the greatest sensitivity and precision available, experiments could be done under carefully-controlled conditions, and human intervention would be easily available to repeat or modify experiments on the basis of initial data. Careful examination of the samples could shed light on the possible existence of past (fossil) life, and the sample materials could be preserved for future experiments using better equipment and new ideas.

These objectives cannot be attained by a single experiment or even by the complete set of experiments on a single mission. Instead, the answers to such major problems will only be found by establishing constraints developed by integrating the measurements from many different instruments flown on different missions. The Mars missions recommended for the SSEC's Core and Augmented Programs will address these questions in depth.

A variety of missions are needed to study the planet in different ways. Orbiting spacecraft can carry out comprehensive global and regional geoscience mapping by making remote measurements of the morphological, physical, and chemical properties of the surface. Orbiting spacecraft can also determine such global properties as topography, gravity, magnetic fields, and the structure of the atmosphere and ionosphere.

These global and regional data are required for comparative planetology. They also provide the spatial context for subsequent, more sophisticated *in situ* measurements on the martian surface or within the atmosphere. For instance, determining the internal structure of the planet requires seismic data, which cannot be

acquired by remote sensing, but must be obtained from a network of surface stations that can operate over long periods of time. Such a network can also provide long-term meteorological data at the surface.

Other *in situ* investigations can provide information on the nature of martian surface materials, the interaction between the surface and the atmosphere, the stratigraphic and depositional history of surface materials, atmospheric composition and evolution, and biological properties. These *in situ* measurements may be carried out in many ways: by probes into the atmosphere or onto the surface, by hard landers, by soft-landed laboratories, or by mobile laboratories. These data also provide ground truth for comparison with the orbital remote sensing data.

While some martian processes can only be studied *in situ*, the return of samples from Mars for detailed study and analysis on Earth is by far the most accurate way to make many types of critical measurements. For example, the return of unsterilized martian materials could provide otherwise unobtainable data on the absolute chronology of martian rock units, on the presence and nature of contemporary or fossil life, on surface/atmosphere interaction processes and rates, and on the composition and evolution of Mars' crust and mantle. To meet these objectives, a sample return mission must provide a variety of rationally-chosen samples from carefully selected areas; the mission must incorporate significant surface mobility in order to achieve these goals.

The SSEC Core Program for Mars Exploration

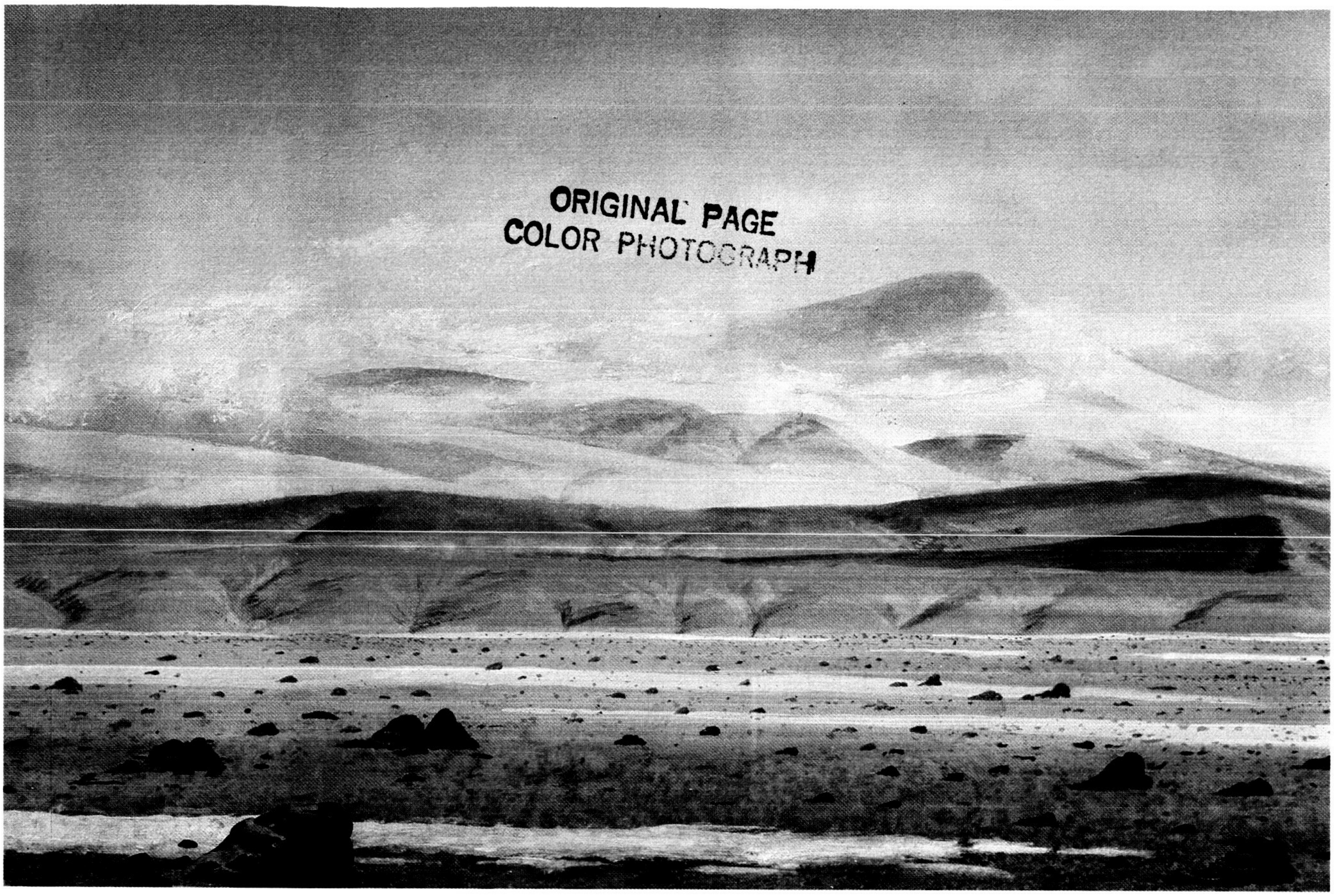
Between 1975 and 1980, virtually all of the Mars missions considered by NASA were complex, comprehensive efforts in which the science return would have been maximized by flying large and complex payloads as a logical extension of the *Viking* experience. In the formulation of the Core Program, such complex missions as sample returns and soft-landed automated laboratories had to be excluded for reasons of cost–not because of low scientific priority. Accordingly, the SSEC recommended that the Core Program be augmented at the earliest possible opportunity by including challenging, high-priority missions of this type.

Key elements of the recommended Core Program involve the exploration of Mars; candidate missions include the *Mars Observer* (now under development), together with the future planned *Mars Aeronomy Observer* and *Mars Network Observer*.

The *Mars Observer* is the first *Planetary Observer* mission. It addresses its geoscience and climatology objectives by remote sensing from a near-polar circular orbit. Specific objectives are to:

- Determine the global elemental and mineralogical character of the surface material.
- Define globally the topography and gravitational field.
- Establish the nature of the magnetic field.
- Determine the time and space distribution, abundance, sources, and sinks of volatile material and dust over a seasonal cycle.

The icy polar hills of Mars, where stratified deposits may hide layers of permafrost that could provide abundant water for explorers.



- Explore the structure and circulation aspects of the atmosphere.

The *Mars Observer* mission was begun as a new planetary start in the fall of 1984; it is scheduled to be launched in 1990 to map Mars for a full martian year (about two Earth years).

The *Mars Aeronomy Observer*, a mission under study but not yet approved, is planned to be undertaken during the 1990s. It will expand knowledge of the martian upper atmosphere and ionosphere by making measurements from a highly elliptical orbit for a full martian year. Specific objectives are to:

- Determine the diurnal and seasonal structure variations of the upper atmosphere and ionosphere.
- Determine the solar wind interaction with the atmosphere.
- Measure the escape rates of atmospheric constituents and infer what these rates indicate for the history and evolution of the martian atmosphere.

The *Mars Network Observer* mission, also under study, will establish on the martian surface a widely distributed array of seismic and meteorological stations to operate for several years. Such a network might be emplaced by hard landers or by penetrators. (Penetrators are missile-like instrumented probes that impact the surface vertically at high velocity. These probes bury themselves to a depth

Exobiology and Future Mars Missions

There is a confluence of scientific evidence from geology, climatology, and planetary formation studies which suggests that the climate on early Mars was quite different from present martian conditions. Mars may have possessed a warm, thick carbon dioxide atmosphere, with liquid water common on the surface, similar in many ways to primordial Earth. During this epoch, billions of years ago, the surface of Mars could have been conducive to the origin of life.

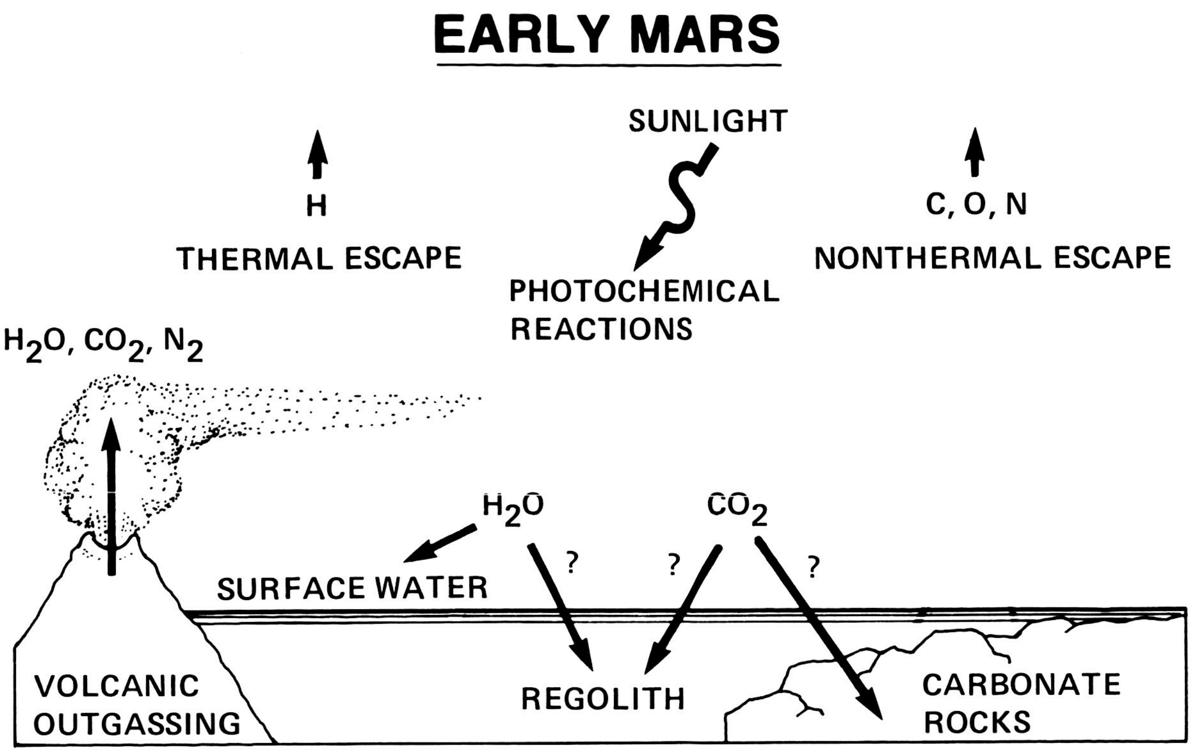
There are many geologic features on Mars that suggest the past presence of ground ice or water. These include topographical features such as patterned ground and features that suggest the "fluid" flow of soil material. In addition, there are channels and valley systems that appear to have been carved by flowing water.

The dendritic valley systems, in particular, attest to the fact that copious amounts of liquid water once flowed on the martian surface. It is clear from the length and size of the valley networks that liquid water existed at the surface. This in turn implies that the martian surface temperatures were considerably warmer, and atmospheric pressures much higher, than they are today. Current estimates indicate that about one atmosphere of carbon dioxide was required to warm primordial Mars above the freezing point. Some of these fluvial features occur in terrain that is heavily cratered, indicating that this warmer climatic regime probably dates back several billion years.

This view is supported by theoretical considerations which suggest that during the first several hundred million years after the formation of Mars and Earth, the atmospheric composition and pressure on these planets was determined primarily by volcanic outgassing of carbon dioxide, water, and nitrogen. In fact, Earth, Venus, and Mars may have all undergone initial periods of outgassing and crust formation that resulted in similar surface conditions. On Earth, the atmospheric carbon dioxide formed carbonate rocks which eventually were recycled back into the atmosphere. On Mars, the carbonate rocks could have been recycled due to volcanic activity, but, eventually, as the volcanism subsided in intensity and became regional in scale, the recyling would cease, depleting the atmosphere.

We know from the fossil record that life on Earth evolved and reached a fair degree of biological sophistication within the first 800 million years. The time interval for the origin of life was probably much shorter, but the absence of an extensive fossil record from this period prevents any determination. It is entirely possible, then, that life also arose on Venus and Mars during their early clement epochs. Subsequent planetary evolution, however, seems to have maintained habitable conditions only on Earth. The record of the origin and early evolution of life on Earth, and possibly on Venus, has been obscured by extensive surface activity. On Mars, the situation is quite different, and large fractions of the surface date back to this early time period. Hence, it is entirely possible that even if no life exists on Mars today, it holds the best record of the chemical and biological events that led to the origin of life.

There are many areas in which a Mars rover could search for evidence of an ancient martian biota, including the bottoms of the outflow channels and the valley networks that lace the ancient terrain. Studies that might be performed on Mars, and in much more detail on returned samples, include the assessment of the distribution and evolution of the biogenic elements (carbon, hydrogen, nitrogen, oxygen, phosphorus, sulfur) and compounds (e.g., water, carbon dioxide, nitrous oxides). Organics or reduced carbon compounds may be found in the deep sediments. Of particular interest are the sediments found on the floors of some of the martian equatorial canyons, which appear to have been deposited in lakes. Studies of the primordial martian sediments could yield detailed information on past martian organisms and the processes instrumental in the origin of life and could vastly extend our understanding of life as a planetary phenomenon.


EARLY MARS
SUNLIGHT
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THERMAL ESCAPE
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C, O, N
NONTHERMAL ESCAPE
H_2O, CO_2, N_2
H_2O
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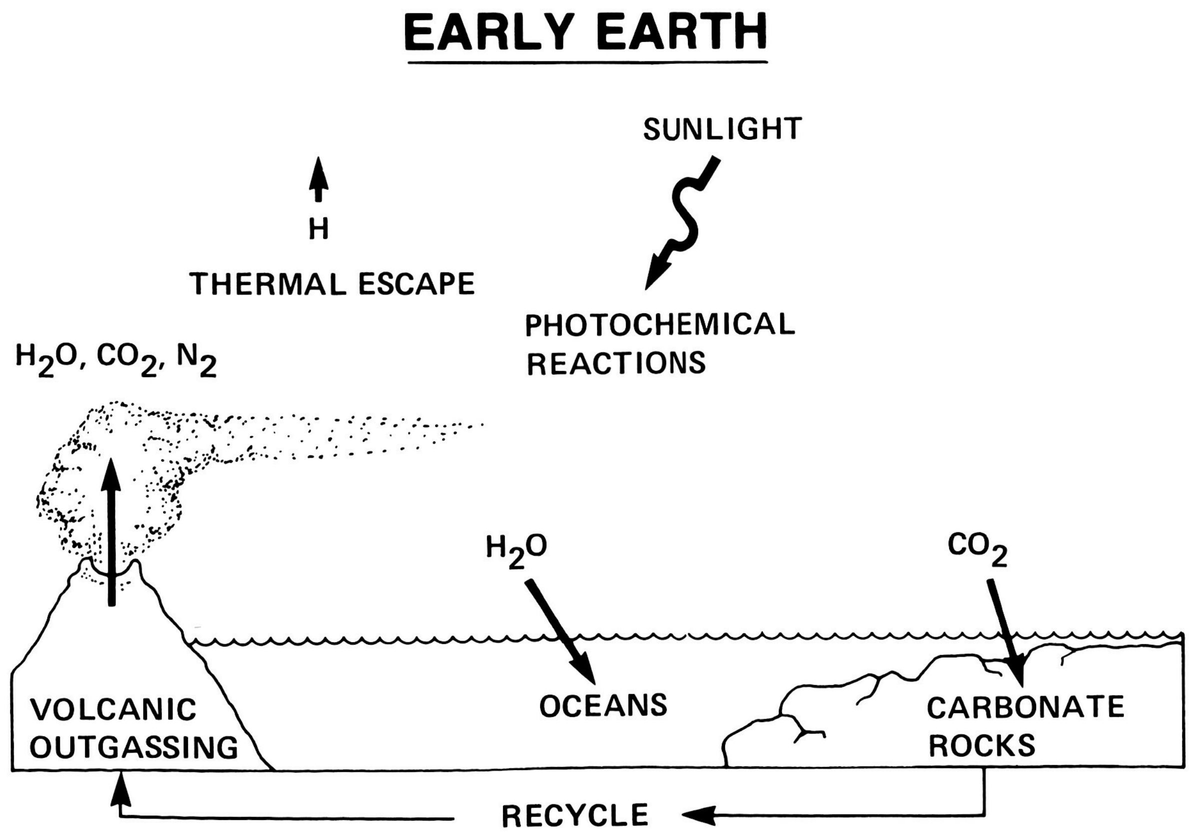
SURFACE WATER
VOLCANIC OUTGASSING
REGOLITH
CARBONATE ROCKS


EARLY EARTH
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THERMAL ESCAPE
PHOTOCHEMICAL REACTIONS
H_2O, CO_2, N_2
H_2O
CO_2
VOLCANIC OUTGASSING
OCEANS
CARBONATE ROCKS
RECYCLE

A lander equipped with an elastic loop-wheeled mobility system (ELMS) gathers a sample from a remote area of the martian surface.

of several meters beneath the surface, while a detached afterbody remains at the surface, making meteorological observations and relaying data to an orbiting spacecraft.)

Specific objectives of the *Mars Network Observer* are to:

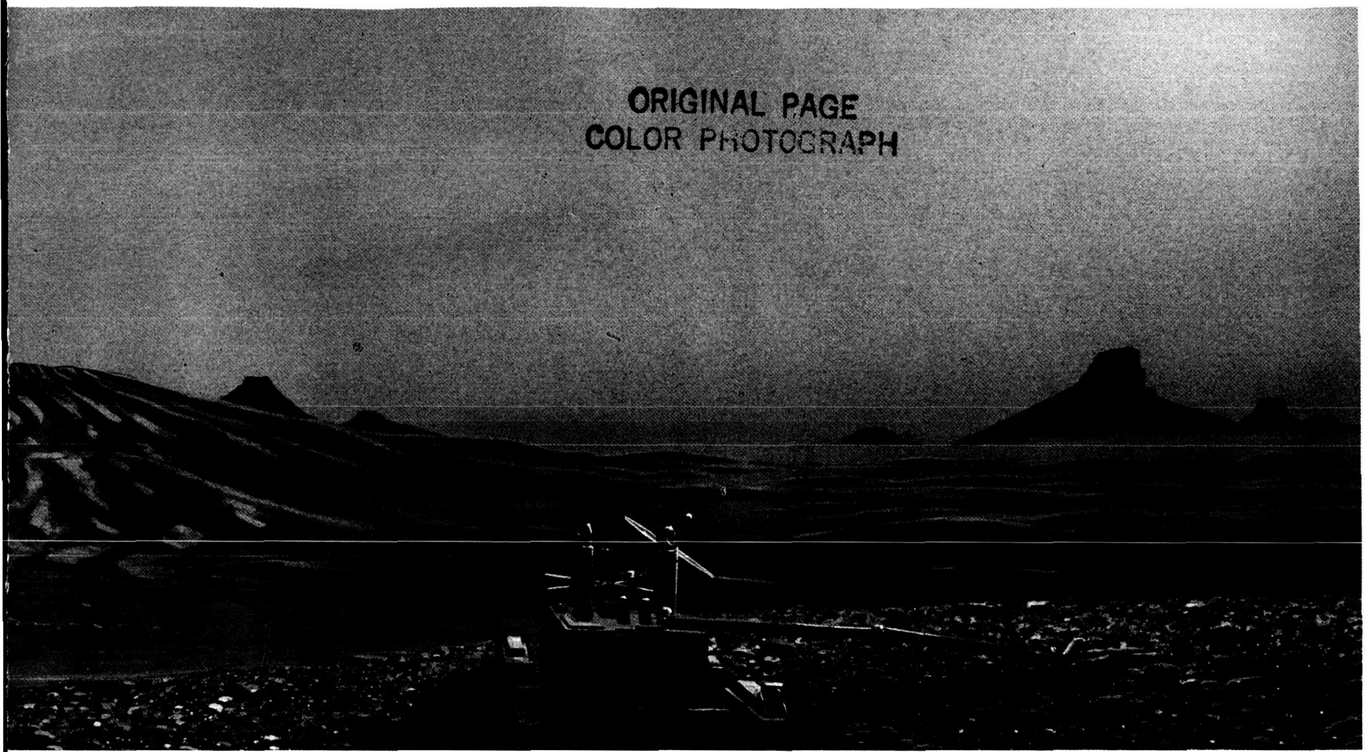
- Determine the seismicity and internal structure of Mars.
- Measure the local atmospheric temperature and pressure continually for a Mars year at several locations to provide understanding of the general circulation of the martian atmosphere.
- Determine the chemical composition of martian near-surface material.

Much additional work is required to define this mission fully; the details will depend in part on the results from the *Mars Observer* mission and on the status of planning for a *Mars Sample Return* mission.

Objectives for Studying Returned Martian Samples

The overriding objective of a *Mars Sample Return* mission is to obtain documented samples collected from a known location on Mars, and the fact that the location of the samples is known is as important as the samples themselves. Without a known location, much of the information extracted from any sample cannot be used to understand the origin of whatever world the sample came from.

The need to go to Mars and collect our own documented samples



is underscored by the current tantalizing controversy over the possible martian origin of a group of rare meteorites whose unusual properties suggest a planetary–and possible martian–origin. Without unquestioned martian samples to compare them with, the question of their origin cannot be firmly settled.

Documented martian samples from known locations are uniquely capable of providing an absolute chronology for the planet. They will also be required to recognize and to characterize any past or present martian life. In addition, the detailed chemical and isotopic information contained in the samples will allow us to determine the extent and timing of chemical differentiation of Mars, as well as the nature of the chemical and physical processes that have formed the planet's atmosphere and shaped its surface.

Analysis and study of samples returned to Earth are unique because they:

- Can be performed by a great variety of scientists with current state-of-the-art technology. (The sensitivity, precision, and scope of laboratory analyses are constantly and rapidly improving.)
- Permit iterative, imaginative experiments that can be based on prior results, including unexpected ones.
- Allow effective separation and concentration of mineral phases, based on the specific properties of the sample.
- Permit many different analyses on the same sample.
- Permit the deferral of certain experiments, if necessary, until better analytical technology or understanding is available.

A *Mars Sample Return*: Just What Kind of Mission?

Before the detailed planning for a *Mars Sample Return* mission can be started, some important decisions have to be made about just what kind of mission it will be. Where should it land? Is more information needed about possible landing sites? How much sample should it return? Should it only collect samples from near the landing site or should it collect materials from farther away? What other experiments should it carry out on the surface? Should the sample be sterilized to avoid any danger of contaminating Earth with dangerous microbes? These questions must be answered first; without answers, it is impossible to plan the mission or to design the spacecraft.

Studies of sophisticated unmanned missions, including sample returns, to explore Mars in great detail have been made periodically for nearly two decades. After the successful *Viking* mission, these studies became more focused and definitive. The most recent study, whose results are included in this chapter, was carried out jointly by the Jet Propulsion Laboratory, the NASA Johnson Space Center, and Science Applications International Corporation. This study included recent and anticipated technical developments that would improve the mission and the sample collection operations.

Some of the basic conclusions reached for planning a *Mars Sample Return* mission are:

- About *five kilograms of total sample* should be returned.
- The mission should *include a roving vehicle* (rover) with a traverse range of tens of kilometers.
- Only those investigations and experiments *needed to support sample collection* should be carried out during the mission.
- Samples should *not be sterilized.*
- *No further site certification* is needed on the mission. Available *Viking* data are adequate to select a landing site.
- A large number of *new technical developments are needed* to make the mission possible.
- The *Space Station is not necessary* to make the mission possible, but it could provide important support functions.

The flexibility of laboratory sample analyses and the resulting confidence in results are largely due to the high analytical precision and to the greater control of experimental parameters possible in a laboratory.

However, the ability to address key scientific questions by laboratory analyses on Earth depends critically on how well the original condition of the martian samples can be preserved during the sampling process and the return trip to Earth. Proper precautions for sample protection are required to preserve the chemical and physical evidence indicative of the *in situ* conditions under which the sample was collected.

The following kinds of research on returned martian samples will help answer major questions about Mars:

1. MINERALOGY/PETROLOGY/GEOCHEMISTRY

Studies of the mineral composition, mineral chemistry, texture, and bulk chemical composition will define the physical and chemical history of the rocks. The detailed comparison of textural properties, mineral compositions, volatile compositions, and the distribution of

elements within the rocks will provide evidence for understanding basic planetary processes that range from crustal formation and volcanism to chemical weathering at the surface.

2. *TRACE ELEMENT CHEMISTRY*

Numerous trace element signatures have been identified as tracers for terrestrial and lunar geochemical processes. Determination of these elements will yield evidence about the original bulk composition of Mars, the nature of subsequent physical and chemical differentiation within the planet, the martian internal heat sources, the temperatures and pressures of internal processes, and the nature and amount of meteoritic material impacting Mars during the geologic past. Our past experience with both terrestrial and extraterrestrial rocks shows that such analyses can be combined with other geologic information to unravel the complex evolutionary history of Mars and its surface materials.

3. *ISOTOPIC STUDIES*

Precise measurements of specific *isotopes* (atoms of the same chemical element with different atomic weights) in planetary surface materials will allow us to attack a wide variety of historical and geochemical problems. Long-lived radioactive elements and their daughter products provide isotopic ages for rocks that represent the only means for establishing an absolute chronology. The isotopic compositions of stable (non-radioactive) chemical elements in rocks and minerals (especially such elements as hydrogen, oxygen, nitrogen, silicon, carbon, and sulfur) provide powerful geochemical tracers that can be used with the chronological data to understand the past condition of the interior of Mars as well as more recent surface processes. Other isotopic anomalies, produced by the decay of extinct short-lived radioactive elements, can provide evidence for formation conditions and time scales in the early solar system, even before the formation of Mars and the other planets.

4. *NOBLE GAS STUDIES*

Analyses of rocks and minerals for the *noble gas elements* (helium, neon, argon, krypton, and xenon) and their isotopes are essential for understanding the internal differentiation history of Mars, the evolution of the planet's relatively primitive atmosphere, and the interaction of Mars with solar and cosmic radiation. Such data from martian surface materials will provide powerful tools for understanding the evolution of the planet's surface and interior. From our experience with lunar samples, meteorites, and terrestrial rocks, xenon isotopes are expected to be the most versatile, because the isotopic patterns may reflect several processes–extinct short-lived isotopes, the fission of both long-lived and extinct isotopes of uranium and plutonium, and the mixing effects of various planetary reservoirs of gas.

5. *PHYSICAL PROPERTIES*

Samples will be examined for evidence of remanent magnetization

arising from past martian magnetic fields, as well as for a variety of other physical properties, such as grain size distribution, density, porosity, thermal conductivity, and seismic wave velocity. These measurements will provide basic data for developing and testing various physical models of Mars. Physical and chemical properties of the surface regolith materials must also be understood in order to determine: (1) their capacity to adsorb and release gases (particularly water and carbon dioxide) and the rates of interchange of these gases between the regolith and the atmosphere; (2) how they reflect and absorb electromagnetic radiation. Because surface/atmosphere volatile exchange is a fundamental mechanism governing the martian climate, surface property measurements on regolith samples will make it possible to reanalyze and substantially extend the climatological measurements made by the *Mars Observer*.

6. BIOLOGICAL STUDIES

Study of returned martian samples on Earth provides an excellent opportunity to look for evidence of both past and present martian life. **To protect the integrity of this critical information, both geochemical and biological, contained in the returned sample, sterilization by any method must be avoided.** Because any martian organisms included with the returned sample might be killed by exposure to the high pressure, high water content, and high oxygen content of the terrestrial atmosphere, the most promising techniques for life detection may be based on chemistry and morphology, rather than on evidence of metabolism. Such experiments would include microscopic and petrographic examinations, perhaps using stains or fluorescence techniques that can detect small isolated areas of carbon within the sample.

These experiments on returned martian samples are crucially important. If any life-forms (viable, dormant, recently dead, or fossil) should be detected in the returned sample, the direction of our future exploration of Mars would be completely changed.

Science Considerations for Mission Design

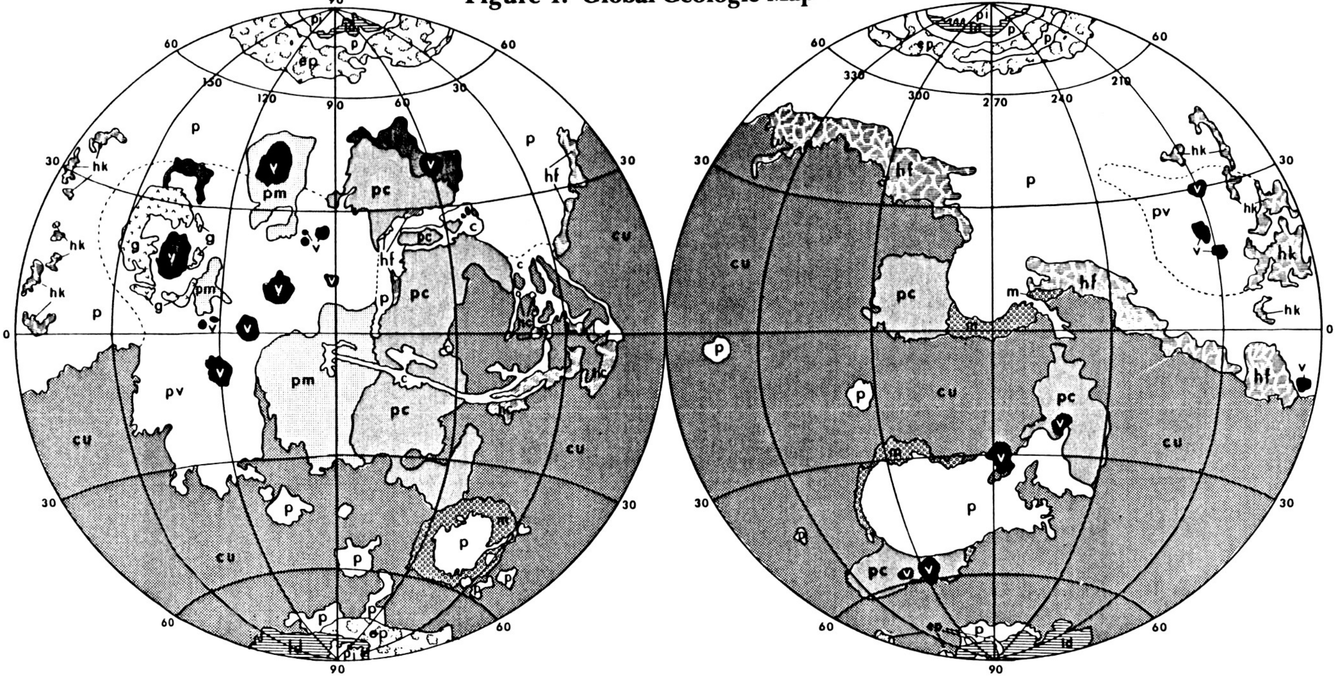
A sample return mission to Mars is very complicated, and there are many ways to carry it out. The following set of working premises has been developed to define mission requirements and to limit the number of mission options to a few that can be studied and compared in detail. **These premises are based on the work of numerous NASA studies and science working groups, and the SSEC endorses them as providing a necessary framework for developing a feasible and scientifically rewarding mission.**

- The sample return mission will not include activities that are specific objectives of other missions in NASA's Core Program.
- All measurements that can be done on returned samples should be done on Earth. Only those measurements that must be done in place, such as pH and volatile content, should be done on Mars as part of the sample collection operations.

- The key geologic units to be sampled on Mars are: young volcanic units; intermediate age volcanic units; ancient cratered units; layered units; polar units.
- Key materials to be sampled on Mars for return to Earth are: fresh igneous rocks; weathered igneous rocks; breccias (fragmental rocks often produced by meteorite impacts); sedimentary (layered) rocks; regolith (loose surficial material, often formed by weathering); wind-blown sand and dust; and possibly atmosphere.
- The prime sampling objective of a first mission is to collect both fresh and weathered samples of the most abundant types of materials in the near vicinity of the lander.
- Special sampling tools and containers are required in order to sample a wide range of martian materials that include hard rock, regolith, non-cohesive materials, and possibly atmosphere.
- Significant sampling mobility (at least 100 meters radius), significant sampling time (several months), and a reasonable returned sample mass (at least four kilograms), are required to properly sample the materials available at a single *Viking*-like landing site.
- To be assured of being able to reach outcrops of fresh igneous rocks from the landing site, it will be necessary to have even more sampling mobility, ranging from one to two kilometers from the landing site in young volcanic regions to ten to 20 kilometers from the landing site in ancient cratered regions.
- The environment imposed on the samples during return to Earth should maintain, as closely as possible, the conditions which the samples experienced on Mars.
- The currently available *Viking* imaging data are sufficient to identify suitable candidate landing sites for sample return missions. Some of these sites are underlain by a single key geologic unit, and some sites have several units in close proximity. No additional imaging is required for site certification.
- The capability to provide a small landing error ellipse (ten to 20 kilometers), combined with fairly extensive sampler mobility (ten to 50 kilometers) would permit sampling of several key geologic units from a single landing site.
- The capabilities developed for a mobile sampler (a rover) could also make it possible to carry out some prime scientific objectives of a surface rover mission. These objectives should be constrained to avoid duplicating those objectives which will be met by study of the returned samples on Earth.

Although proper analysis of any martian sample will provide important new knowledge and understanding about Mars, no single sample, nor any single sampling site, will solve all of the martian problems mentioned earlier, or will even solve any one problem

Figure 1. Global Geologic Map of Mars



Map units are plotted on a Lambert equal-area base. Polar units *include* pi *(permanent ice),* ld *(layered deposits), and* ep *(etched plains).* Volcanic units *include* v *(volcanic constructs),* pv *(volcanic plains),* pm *(moderately cratered plains), and* pc *(cratered plains).* Modified units *include* hc *(hummocky terrain, chaotic),* hf *(hummocky terrain, fretted),* hk *(hummocky terrain, knobby),* c *(channel deposits),* p *(plains, undivided), and* g *(grooved terrain).* Ancient units *include* cu *(cratered terrain, undivided) and* m *(mountainous terrain).*

completely. On the other hand, obtaining a large number of samples, from a large number of landing sites, is not feasible because of the limited operational capability of a rover and the cost of numerous sample return missions.

It is necessary, therefore, to define a mission strategy that maximizes the probability of selecting samples that answer the widest diversity of fundamental questions within reasonable operational and budgetary constraints. This strategy must include evaluation of: (1) the criteria for site selection; (2) the acquisition of adequate individual samples; (3) the degree of mobility required by the sampling device; (4) scientific and operational requirements for the rover itself.

SITE SELECTION: The quality of scientific information obtainable from a sample return mission is crucially dependent on the proper selection of sampling locations. The mission recommended in this chapter has as one of its most significant attributes the ability to reach and return from almost any desired part of Mars, including the polar regions.

For the first sample return mission, the sampling sites on Mars should be selected to attack basic planet-wide problems rather than to characterize specific surface features detected on images, no matter how intriguing such features may be. Other factors involved in judging the relative merits of the candidate landing sites are: (1) the uncertainty associated with targeting the lander to a specific place; (2) the proximity of key geologic units; (3) the probability of locating fresh or recently-exposed rocks; (4) the planned range of the rover. Landing sites that promise access to more than one interesting terrain or geologic unit offer clear advantages.

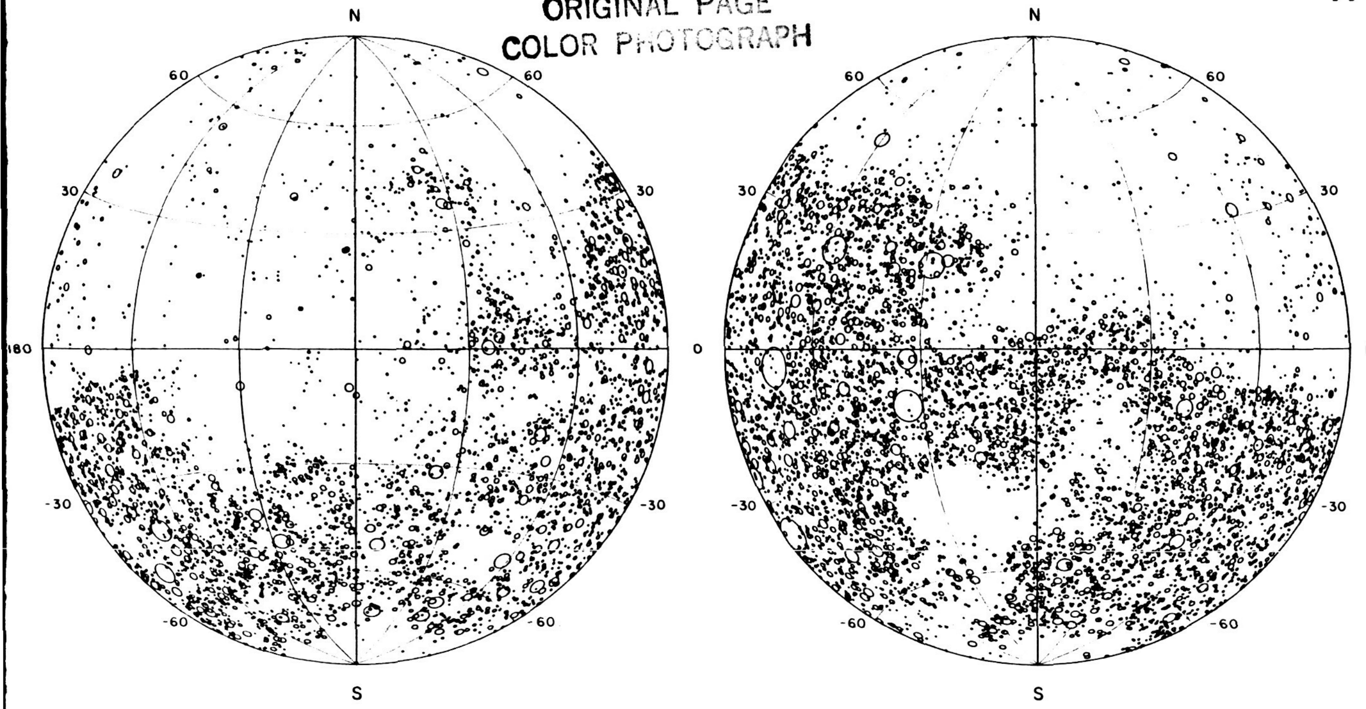


Figure 2. Global Map of Mars Showing Cratered and Uncratered Terrain

Unfortunately, such sites may also pose the most significant landing hazards and obstacles to rover mobility.

Several basic geologic units can be seen on the global geologic map of Mars (Figure 1). There is a striking hemispheric asymmetry on Mars; two very different regions are separated by a great circle inclined at roughly 20 degrees to the equator. To the south of this boundary lie the higher-altitude, highly cratered, ancient terrains; to the north lie the lower-altitude, relatively uncratered, younger plains (Figure 2). The four major geologic provinces of Mars are:

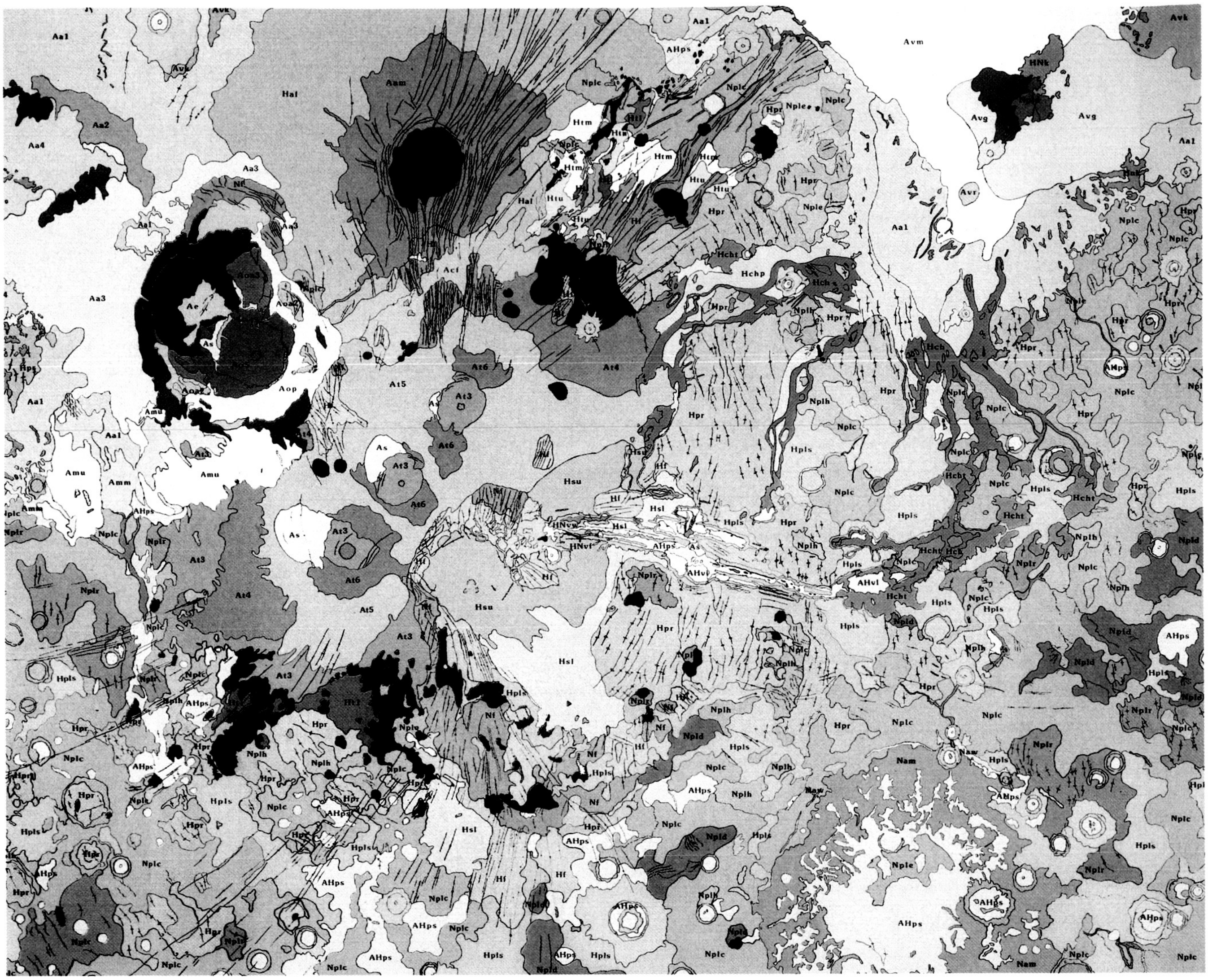
1. *ancient units* composed of heavily cratered terrain (with undivided, densely to moderately cratered uplands) and mountainous terrain with rugged basin margin material–probably eroded impact basin ejecta.

2. *volcanic units* such as shields, domes, cones, plains, and cratered plains that resemble lunar maria.

3. *polar units* composed of permanent ice, layered deposits, and etched plains.

4. *modified units* composed of hummocky terrain with chaotic, fretted, and knobby features, interspersed with channel deposits, plains, and grooved terrains.

Rocks from the *ancient cratered units* are expected to consist of several types: (1) impact-produced breccias containing fragments of ancient rocks; (2) impact melts; (3) ancient volcanic and metamorphic rocks. From these samples we expect: to learn about the petrologic and geochemical evolution of the early martian crust; to deduce the time of formation of the martian crust; to place limits



Preliminary geologic map of the western equatorial region of Mars.

on the composition of the planet, its mantle, and its core; to decipher the early bombardment history of the planet; to constrain the nature of an early martian atmosphere or hydrosphere; and to determine the characteristics of impacting asteroidal material.

Rock samples from the *volcanic units* are expected to include lavas with a wide range of chemical compositions and ages. From geochemical, petrologic, and age-dating studies of these rocks, we expect to be able to decipher the thermal history of the martian mantle, the extent of its chemical differentiation, and the processes involved in near-surface chemical fractionation. Moreover, we can expect to establish more narrow limits on the bulk composition of the planet; to determine the fundamental properties of that region of the solar nebula from which Mars accreted; to determine the ages of lavas erupted onto the surface (which will in turn provide ground truth for ages based on cratering statistics, allowing us to extend these ages to the rest of Mars); and to establish the nature of martian volcanic gases and the extent to which these gases have contributed to building up the martian atmosphere.

Rocks from the *polar units* are expected to be a series of sedimentary strata that may provide a record of past and present atmosphere/surface interactions; because of the abundance of water ice at the poles, these layered rocks may also be important to biological studies.

These three basic geologic units of the martian bedrock have been transformed into *modified units* by both crustal and surface processes to produce canyons, channels, chaotic terrains, fretted terrains, hummocky terrains, and other striking and unusual landforms. Some of these modifications may enhance sample selection because the erosion and deposition involved may have brought otherwise inaccessible materials within the reach of a sampling device. Sampling close to young impact craters, as we learned from the *Apollo* missions to the Moon, increases the chances of obtaining subsurface material as fresh rock fragments that have not been deeply altered by long exposure to the martian atmosphere. Areas of major sedimentation may provide the best chance of collecting samples that contain evidence for past life. Finally, any sampling site on Mars will contain a variety of both wind-blown and impact-derived debris, which will increase the probability of sampling both distant and local materials.

Samples of atmospheric gases and soil volatiles can also be collected at any site to provide information about atmosphere/surface interactions, on the extent of planetary degassing, and on the degree to which Mars has retained its primordial gases.

Based on our present understanding of Mars, the key geologic units with the highest priority for sampling are: young volcanic units; intermediate age volcanic units; ancient cratered units; layered units; and polar units.

The key types of materials that must be sampled in these units and returned to Earth are: fresh igneous rock; weathered igneous rock; breccia; sedimentary (layered) rock; regolith; wind-blown dust; and atmosphere. The acquisition of such samples from these key geologic units will provide a broad sampling of the planet and will accordingly address planet-wide problems.

Studies of possible sampling sites indicate that a wide range of materials can be acquired at a few well-chosen landing sites located at the boundaries between major geologic units. Natural features at these sites, such as craters, landslides, channel cuts, and channel deposits, can be used to obtain the widest diversity of samples in the near vicinity of the lander. Eventually, several sample return missions would be needed to provide coverage of all important planet-wide units, but a single sample return mission, from a carefully chosen and documented site, will produce a major revolution in our understanding of Mars.

Earlier Mars missions have provided a data base that is already adequate to plan and undertake a sample return mission. We have global photomaps of Mars at sub-kilometer resolution, together with substantial areas of imaging coverage with resolutions of better than 100 meters. During the extended *Viking* mission, numerous swaths of very high resolution (15 to 20 meters) contiguous images were also acquired for the specific purpose of selecting landing sites for a

sample return mission. There is thus no need for any new precursor imaging mission or for a concurrent imaging orbiter associated with the sample return mission itself.

These blocks of high-resolution *Viking* images have already been studied to determine whether they include sites at which key geologic units can be sampled and to define the mobility required to sample these key materials. Numerous candidate landing sites have been identified. Some sites are underlain by a single geologic unit, while others have several units in close proximity.

The *Mars Observer* mission, to be launched in 1990, will provide more information to support the final choice of a landing site. The most important inputs from this mission will be altimetry, radar data, and multispectral data that will provide geologic, chemical, mineralogical, and topographic information about the martian surface.

SAMPLE ACQUISITION: We already know that Mars will provide a wide range of physically different materials to sample. The surface materials observed at close range at the *Viking Lander* sites range from blocks of hard, consolidated rocks (both fresh and weathered) to assorted loose, particulate materials (soils, dune materials, dust, etc.). Each of these materials has its own special scientific importance, and it will be necessary to sample all of them to carry out an adequate sample return mission.

It is also clear that a variety of special tools will be needed to select, obtain, and handle such physically diverse martian materials as hard rock, partly consolidated regolith or soil, loose material, and atmospheric gas. A drill capable of obtaining cores from hard rocks is essential to penetrate the weathered exterior of bedrock surfaces and to collect the unaltered material beneath. Only in this way can we be certain of obtaining the fresh igneous rocks that are crucial to a wide range of geochemical studies. A core tube will be needed to sample the surface regolith, and a sampling arm will be needed to collect fragments of hard rock as well as loose soils or sand from the surface.

The use of such tools on the surface of Mars requires additional capabilities—especially the ability to see and to make rough assessments of specimens before collection. An imaging device on the sampler, linked to some type of robotic capability, is essential if the sampling tools are to be used efficiently and in a semiautonomous manner. A capability for multispectral measurements, incorporated into the imaging system, can provide mineralogical information about the surface under study, while any one of several instruments could provide simple elemental composition measurements. Both types of information would be exceedingly valuable aids to sample selection. Some kind of capability to estimate rock hardness and density would be similarly valuable in determining the degree of bedrock alteration.

The fundamental constraint on planning a sample return mission is the decision as to how much sample is to be collected and returned. This consideration leads to the further question, "How much sample is enough?" The answer depends considerably on the science experiments to be performed on it. Electron microscope

studies can be done with micrograms, while measurements of thermal, electrical, or seismic properties may require closer to a kilogram.

Our experience with meteorites and lunar samples has shown that as little as a few grams can be used effectively to provide an important yield of diverse scientific information. Therefore, a sample collection strategy which maximizes the number of samples weighing 0.5 to ten grams will also maximize the information return by providing the widest possible range of materials, the largest number of locations, and the greatest opportunities for comparative studies. This strategy also implies that all such samples, from both surface and subsurface environments, should be collected, documented, and packaged separately to maintain their integrity during the surface operations and the return to Earth.

Containment procedures for martian samples, both before and during return, are critical for preserving the science information content and for minimizing back-contamination of the samples from the surrounding environment. **The sample environment during the return to Earth should maintain, as closely as possible, the conditions which the samples experienced on the martian surface. The samples should *not* be sterilized, because the heat or chemical treatment needed for sterilization may profoundly affect the samples and the information they contain.**

SAMPLING MOBILITY: Surface mobility for the acquisition of samples is essential to meet the scientific objectives of a sample return mission. It is intuitively obvious that such mobility is needed to assure that a wide range of the most scientifically valuable samples can be collected, and this intuition has been reinforced by our experience with the *Viking Landers.*

Observations at the *Viking* landing sites showed that a wide range of materials, including apparently fresh igneous rocks, were present, but they were just beyond the reach of the *Viking Lander* sampling arm. (Compare this situation with the large variety of lunar samples observed, selected, and returned by the mobile *Apollo* astronauts.) However, all of the major materials present at the *Viking* landing sites *could* have been collected within about 100 meters from the landers.

We can therefore regard a radius of 100 meters as the *minimum* surface mobility required for adequate sampling of a given landing site. This figure may be low. Compared to other areas of Mars, the *Viking Lander* sites seem to show a greater diversity of surface materials and a larger number of surface rock fragments. Other areas of the planet are covered by large patches of sand and show few rock fragments, even in areas where the sand cover is apparently not thick enough to form dune fields. In such an area, surface mobilities of several hundred meters to a few kilometers may be necessary to ensure that fresh bedrock is collected. Because the exact distribution of surface rock fragments cannot be determined from the orbital images of these sites, it is probably wiser to consider the higher ranges of surface mobility in order to be certain of success. (In the discussion which follows, surface mobility is used to

describe the *total traverse length* and not the radius from the landing site.)

The probability of acquiring an acceptable suite of samples from a particular site depends on the landing accuracy, the mobility of the sampler, and the nature of the surface. A large uncertainty in the location of the final landing site, such as the 50 kilometer by 120 kilometer landing error ellipse for the *Viking Landers*, would make it useless to pinpoint an ideal landing site (e.g., the boundary between two different geologic units) on the basis of the orbital imagery with its sub-kilometer resolution. Fortunately, there are good reasons, discussed below, to believe that a future landing can be made much more accurately.

Fresh martian bedrock is an essential part of any sample return mission, but it may not be easy to collect it. Rocks exposed on the surface of Mars are altered by chemical reaction with the atmosphere. In areas where the rocks are old or deeply weathered, it may be impossible to obtain fresh samples of key geologic units except in special locations such as relatively young impact craters, landslides, fault scarps, and other places where fresh subsurface rock has been brought to the surface in relatively recent times. Unfortunately, such areas are also characterized by rugged topography and thus provide obstacles to rover mobility. However, in such areas, both the travel rate and the required travel distance can be reduced.

Regions of relatively young volcanic rocks should provide some of the easiest martian bedrock to sample. Collecting fresh bedrock in such areas requires the least mobility, because exposures of relatively fresh rock are common at the surface and actually form most of the obstacles within a given landing ellipse. Study of the orbital images of such areas indicates that a mobility of several kilometers is sufficient to travel from any random point in a given landing ellipse to the nearest outcrop or young impact crater that can be seen on the orbital images.

By contrast, ancient crustal material may be the most difficult to collect. No outcrops of such materials have been identified on the available images, and it is likely that samples will have to be obtained from blocks thrown out of whichever large, fresh, young impact crater is closest to the landing site. Because such craters are not common, sampling of ancient crustal material may require even longer rover traverses, possibly ten to 20 kilometers, over surfaces that could have many obstacles.

Sample collection traverses have already been studied for several possible martian landing sites, using methods developed for planning the surface activities of *Apollo* astronauts on the Moon, together with actual data from the *Apollo 15* mission. Some of the conclusions of these studies are:

1. The greatest amount of time is consumed in Earth-based decisions and by the sampling operations themselves. Actual travel time required for a simulated 155-day sampling traverse on the martian surface was only 31 hours at an average speed of ten centimeters/second.

2. Adequate sampling of one of the *Viking Lander* sites would require only about 100 meters of mobility but would require several months of time. The estimated returned sample weight is about four kilograms.

3. Extended rover sampling operations with greater amounts of mobility will require a high degree of autonomy in both the sampling process and the rover operation.

4. At several possible martian landing sites, there is a high probability of successfully sampling several different key geologic units if the landing ellipse can be reduced to ten to 20 kilometers and if the sampling rover has a capability for substantial mobility (ten to 50 kilometers).

These findings suggest that it is possible to plan for a rover mobility of tens of kilometers for the first sample return mission, because the actual travel time of the rover does not appear to have a major impact on mission operations. However, the premise that "the prime sampling objective of the first mission is to collect fresh and weathered samples from the vicinity of the lander" still seems appropriate for a first mission. Other possibilities involving the rover, while scientifically important, are secondary to this goal.

ROVER OBJECTIVES: The objective of the surface rover is to support the sample collection. The rover is necessary as a sampling device in order to ensure that a wide enough variety of samples is collected to meet the mission objectives. The primary function of the rover is to provide the mobility necessary to collect a basic suite of samples that includes the most abundant types of material in the vicinity (within 100 meters) of the lander. A secondary function is to enable more extended sampling traverses, returning the samples to the ascent vehicle, once this primary goal is accomplished.

The rover is regarded primarily as a sampling device. It should only have the capabilities necessary for sample examination, characterization, and collection, and these capabilities should not be diluted by adding experiments not related to sample collection. The required rover capabilities are generally those of a human geologist collecting samples in the field. Like a geologist, the rover should obtain multispectral, stereoscopic images at a variety of scales and resolutions and compare them with images derived from previous experience.

The rover should be able to lift samples, to examine their details closely, and to estimate their weight and density, thereby evaluating the amount of weathering. It should carry out simple chemical tests like those made with a geologist's traditional Geiger counter or acid bottle. It should provide this information to Earth so that a decision can be made, either to collect a given sample or to discard it and move on to another.

Although the rover's prime objective is to support sample collection, it is important to note that its capabilities, and the data it collects to characterize possible samples, would also be scientifically important during an extended traverse to analyze and characterize

martian surface materials to a significant distance from the landing site. After the rover has completed its sampling traverses (first in the vicinity of the landing site and then, if possible, at greater distances), the rover could carry out an important and exciting long-distance surface traverse of Mars, making the same observations without collecting samples. Such a post-sampling traverse would provide an important regional context for the sample suite and would also help understand better the complex processes that have taken place on the martian surface.

During this extended mission, the rover should be able to cover a much greater distance than it did during the sample collection phase because: (1) experience will have been gained in its use; (2) no more time will be required for actual sample collecting operations; (3) it can be lightened by discarding the drill and other sampling equipment; (4) it can be operated with less caution and at higher rates of travel.

MISSION CONSIDERATIONS AND OPTIONS: Because a *Mars Sample Return* mission will not be launched before the mid-1990s, it can take advantage of the Space Station and related developments in space capabilities. Earlier studies of sample return missions, carried out in the 1970s, were forced to assume the use of retropropulsion motors and *Viking*-type entry systems at Mars. Such missions were massive and complicated. A typical candidate mission required separate launches of the Sample Return Capsule and the Earth Return Spacecraft from the *Space Shuttle* (using two Inertial Upper Stages or equivalent vehicles), combined with an orbital rendezvous at Mars.

In contrast, more recent studies undertaken in connection with the SSEC recommendations have indicated that rover mobility can be added to a *Mars Sample Return* mission by using the Space Station complex for staging a *Centaur* launch vehicle and by using aerocapture and aeromaneuver techniques for both Mars entry of the lander and for Earth entry of the Sample Return Capsule.

A new study of a *Mars Sample Return* mission was carried out in 1984 by the Jet Propulsion Laboratory (JPL), the NASA Johnson Space Center (JSC), and Science Applications International Corporation (SAIC). As an initial step, the study defined a set of ground rules for the mission that includes the working premises discussed earlier in this chapter. In this mission:

1. Five kilograms of samples are collected by a 400-kilogram Rover and are returned to Earth in a 50-kilogram Earth Return Capsule.

2. A precursor imaging mission is not required for site selection and certification; nor is a separate orbiter required for the mission itself to provide pre-landing imagery and to relay communications from the Rover.

3. The 1996 launch opportunity for Mars is used as a baseline.

4. Several different mission possibilities are considered, including the following alternative options:

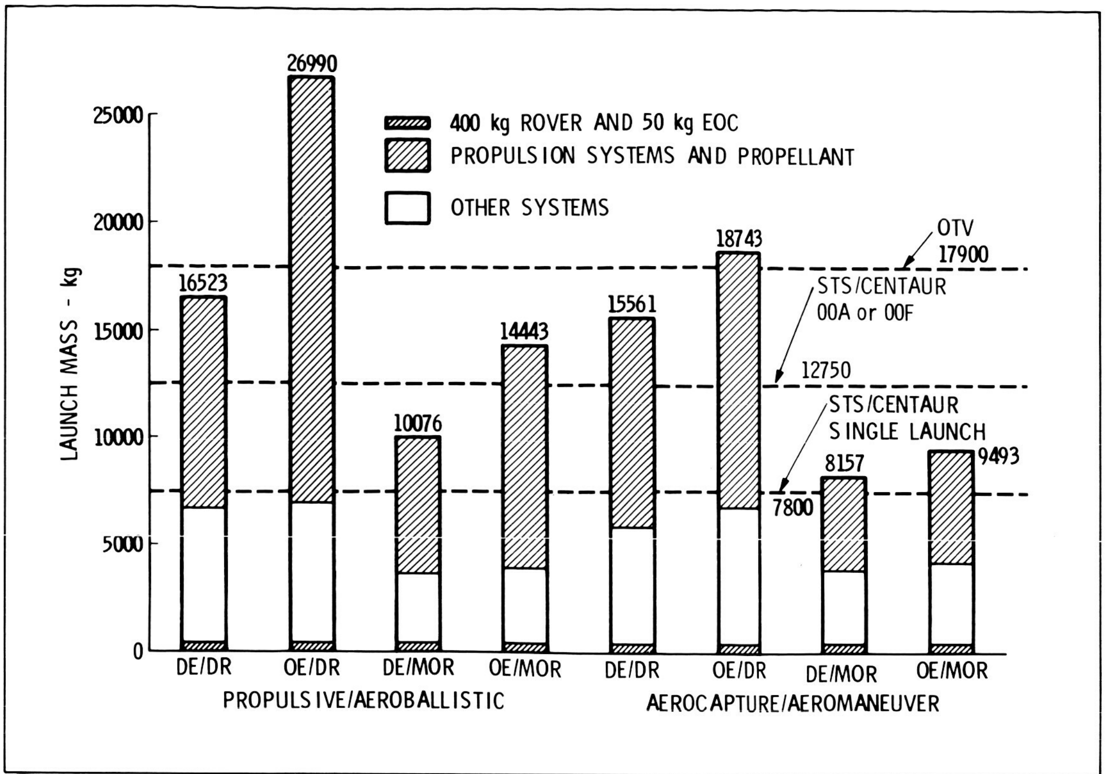


Figure 3. ***MSR*** **Mission Options–Launch Mass Requirements (1996).** Abbreviations: DE = direct entry into Mars atmosphere from Earth, followed by landing; OE = out-of-orbit entry into Mars atmosphere, followed by landing; MOR = Mars orbital rendezvous after ascent from Mars surface; DR = direct return to Earth from Mars surface.

- direct entry (DE) to Mars vs. out-of-orbit entry.
- direct return to Earth from the surface of Mars (DR) vs. return to Earth from Mars orbit following a Mars-orbital rendezvous (MOR).
- insertion into Mars orbit with a propulsive stage, followed by aeroballistic entry to Mars vs. insertion into Mars orbit by aerocapture, followed by aeromaneuver entry.

The spacecraft systems and their components were designed to meet these ground rules. The designs were then carried to the point where it was possible to identify the essential subsystems, their elements, and the maturity of the designs. The vehicles could then be sized and compared to the size of the *Space Shuttle* cargo bay, which was regarded as a prime constraint. Each mission option was then evaluated for its ability to reach candidate landing sites and the accuracy with which a landing could be made.

Some general conclusions from this study are:

1. Options using aerocapture at Mars for orbit insertion, followed by aeromaneuvering during atmospheric entry, require less mass and provide greater landing site precision than options which use the alternate techniques of retropropulsion for orbit insertion, followed by aeroballistic entry only.

DE/DR OPTION	(kg)	OE/MOR OPTION	(kg)
		Orbiter	800
		Propellant	460
		Earth Return Vehicle	210
		Propellant (2.2 km/s)	410
		Earth Orbit Capsule	100
		Total Orbiting Systems	1980
Earth Orbit Capsule	50	Sample Canister	20
Earth Return Vehicle	270		
Propellant: (2.3 km/s)	520		
Ascent Systems	550	Ascent Systems	680
Ascent Propellant (4.2 km/s)	5980	Ascent Propellant (4.5 km/s)	1940
Rover	400	Rover	400
Lander	1300	Lander	1080
Total Landed Systems	9070	Total Landed Systems	4120
Entry Systems	4310		2400
Cruise Support	330		---
Midcourse Propellant	1110		580
Adapter and Bioshield	780		420
Total Launch Mass	15600		9500

Centaur G-prime capability (full tanks) 12750 kg

Figure 4. Preliminary Mass Breakdown of DE/DR Option vs. OE/MOR Option.
For definitions, see Figure 3 and text.

2. Options involving direct return from the surface of Mars to Earth carry a heavy mass penalty, especially in the area of propulsion. This results from the fact that the entire Earth Return Vehicle system must be carried to the surface of Mars and then launched again.

3. Options involving Mars-orbital rendezvous between the Sample Return Capsule and the remainder of the Earth Return Vehicle system have less mass penalty than options involving a direct return to Earth. The reason is that, in these options, only part of the total Earth Return Vehicle system need be landed on Mars and lifted again.

The launch mass requirements for eight different mission options are summarized in Figure 3 and compared to the following assumed launch capabilities.

1. *Shuttle/Centaur:* 7,800 kilograms for a single *Space Shuttle* launch.

2. *Shuttle/Centaur* with on-orbit operations: 12,750 kilograms for (a) a double *Space Shuttle* launch, with on-orbit assembly (OOA), or (b) a single *Space Shuttle* launch with on-orbit fueling (OOF)("topping off" the *Centaur* at the Space Station complex).

3. Orbital Transfer Vehicle: 17,900 kilograms for an Orbital Transfer Vehicle (OTV) now being planned as a future part of the Space Station complex.

Significant mass penalties exist for the options involving direct return from Mars or the use of retropropulsion for orbit insertion at Mars (Figure 4). The figure also shows that a major part of the total spacecraft weight for any sample return mission is taken up by propellant, because the propellant needed to take off from Mars must be carried to Mars and landed there. Missions involving direct return are, as noted above, especially handicapped by the large propellant requirements, which render undesirable a mission whose greatest advantage is its basic simplicity.

If it were possible to produce some or all of the spacecraft propellants on the surface of Mars after landing, a considerable advantage could be gained, especially for missions involving the direct return option. A brief study was made to determine whether it was feasible to extract the necessary propellant from the martian atmosphere, which is 95 percent carbon dioxide (CO_2). In the method studied, the CO_2 is thermally dissociated into carbon monoxide (CO) and oxygen (O); the CO and O are then separated by a solid electrolyte membrane. The oxygen would then become the oxidizer in a propulsion system consisting of methane (CH_4) and oxygen. Only the methane fuel would have to be taken to Mars. With this option, the launch mass requirements could be reduced by about 30 percent for missions involving Mars-orbital rendezvous and about 50 percent for missions involving direct return to Earth.

Because the technology necessary for *in situ* oxidizer production on Mars is still in an early stage of development, **it is not proposed that such a capability be planned for the baseline mission.** Nevertheless, it is clear that such a capability offers major advantages, and this possibility should be considered in future detailed mission studies.

Estimated costs for developing the spacecraft systems and hardware for the three options that can be launched using on-orbit assembly or on-orbit fueling range from $2.1 billion to $2.3 billion (in FY 1984 dollars). These estimates do not include the costs of mission operations, the injection stage for launch toward Mars, *Space Shuttle* operations, on-orbit operations, sample analyses, and post-mission data analysis.

The baseline mission that has been selected for further studies involves: (1) use of aerocapture for orbital insertion at Mars; (2) out-of-orbit entry and aeromaneuvering to a landing on Mars; (3) post-sampling orbital rendezvous around Mars between the Earth Return Vehicle and the Sample Return Capsule, before return to Earth.

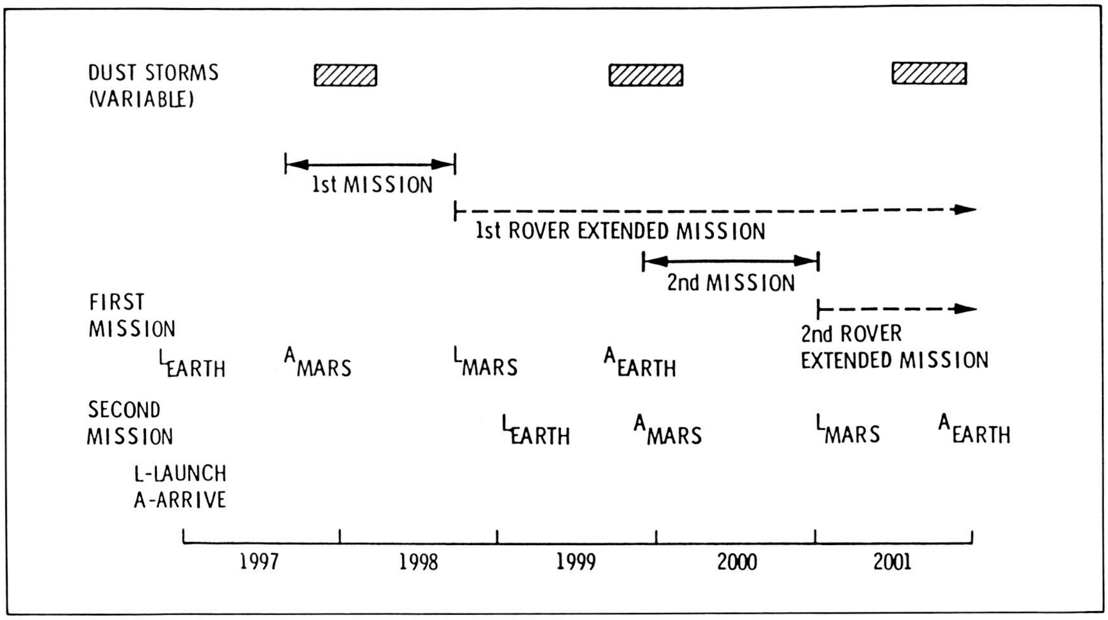


Figure 5. Preliminary Mission Timetable for *MSR*

Aerocapture was selected because it provides a greater savings in mass over the alternate techniques for entering orbit around Mars. Furthermore, because the energy removed to enter orbit is dissipated through atmospheric flight, the method can be optimized for the range of approach velocities resulting from different launch windows over a period of years.

Out-of-orbit entry for a Mars landing was selected because an Orbiter is required for later rendezvous with the Sample Return Capsule. Such an entry also provides more flexibility in landing operations and can improve the accuracy of the landing itself.

The use of aeromaneuvering during entry and landing can produce a landing site accuracy of ten to 20 kilometers, as compared to about 40 kilometers with the alternative method of aeroballistic entry. Aeromaneuvering also creates a wider range of potential landing sites; any place on the entire planet can be reached. The alternate technique of aeroballistic entry can only reach sites that lie south of 45 degrees north latitude.

The use of Mars orbital rendezvous after the sample collecting phase provides a considerable savings in mass and also involves a departure system that is safely parked in orbit.

A Mars Sample Return/Rover Mission for 1996-1998

The basic timetable for this mission is shown in Figure 5 and the resulting trajectories are shown in heliocentric view in Figure 6. For a mission launched in 1996, the Earth-Mars travel time is 303 days,

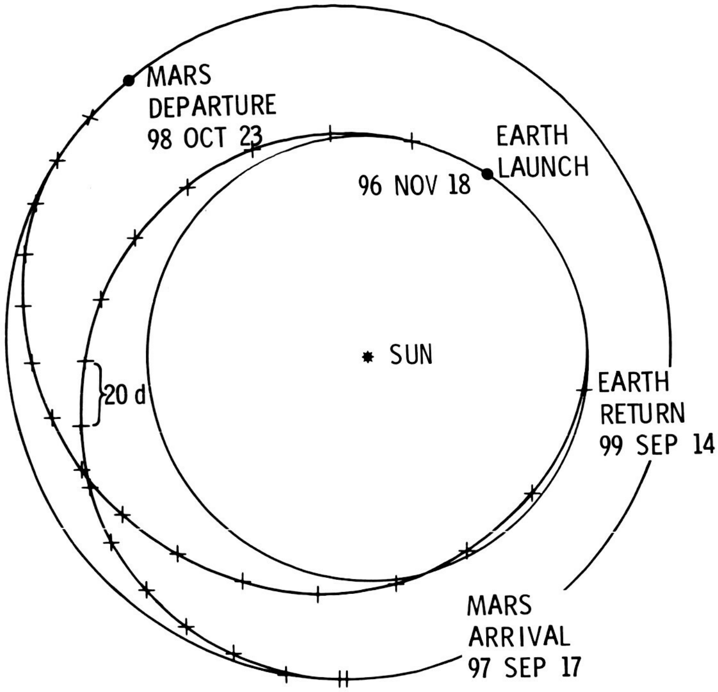


Figure 6. Heliocentric View of Interplanetary Trajectory

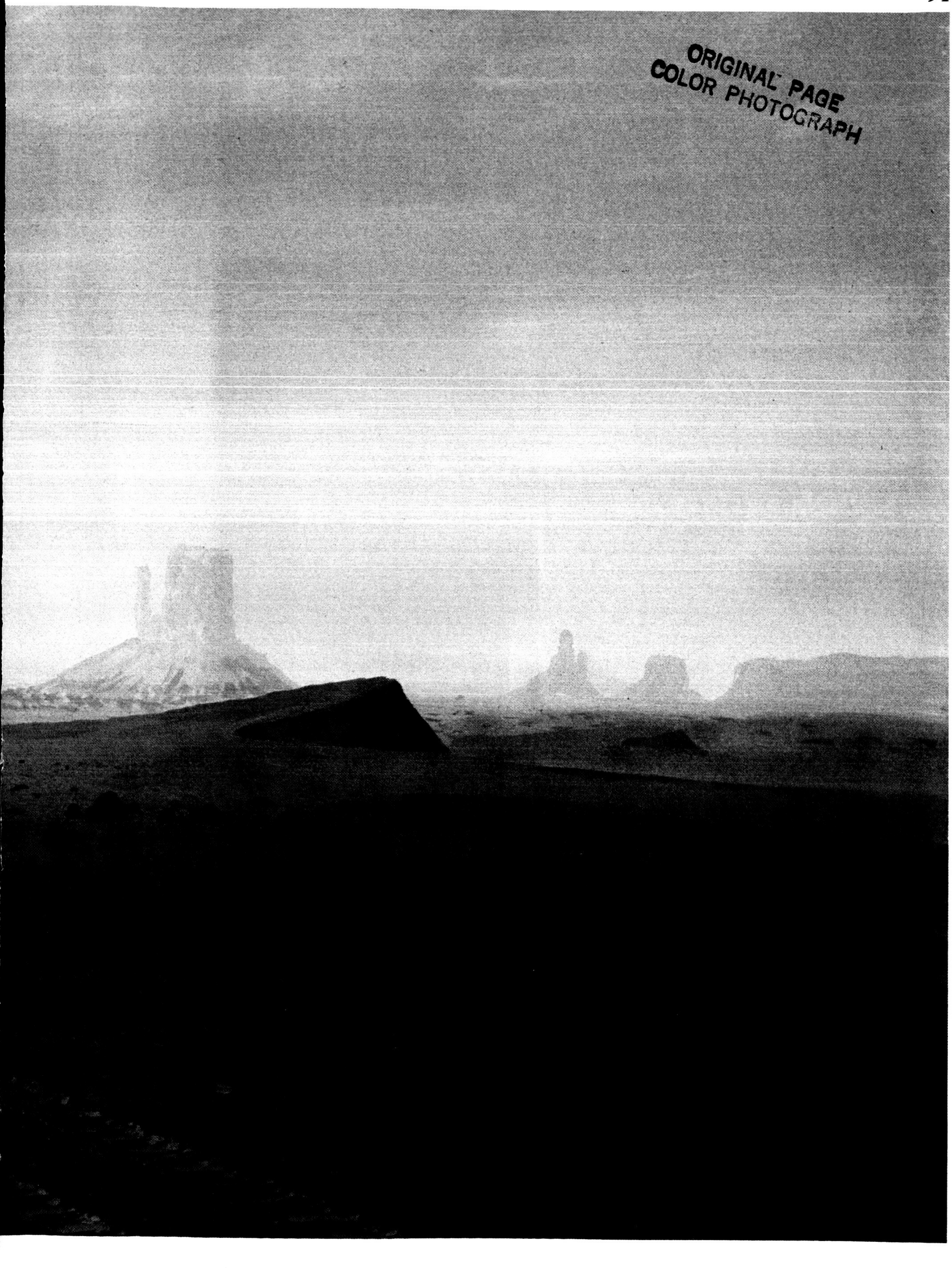
the stay time on Mars is 401 days, and the Mars-Earth travel time is 326 days, for a total of 1,030 days or about 34 months.

The mission sequence is shown in Figure 7, while the details of the total Interplanetary Vehicle System (IVS) for the mission are shown in Figure 8. The IVS consists of seven distinct vehicles and modules, the Mars Entry System (aeroshell, parachute, guidance, etc.) and the Sample Canister Assembly (SCA). Details of the mass breakdowns for the various vehicles are given in Figure 9; the figures include both dry mass and propellant weights. As the mission progresses, the total mass of the original IVS is gradually reduced by such activities as propulsion burns and vehicle jettisons, until only the SCA mass of 20 kilograms is left. This mass, which returns to Earth, includes the five-kilogram sample.

At the start of the mission, the IVS has a mass greater than 7,800 kilograms, and on-orbit assembly is therefore required. This operation does not require the Space Station. Two *Space Shuttle* launches can carry the IVS and the fully-fueled *Centaur* launch stage separately into low-Earth orbit, where they can be assembled together. Alternatively, these operations can be carried out at the Space Station, where the IVS is mated to a *Centaur* (which can then be fueled at the Space Station) or to an Orbital Transfer Vehicle (OTV) based at the Space Station. Once the necessary on-orbit operations (assembly, fueling, and checkout) are completed, the IVS will be launched toward Mars by the *Centaur*.

Upon arrival at Mars, aerocapture techniques will be used to place the IVS into a 560 kilometer by 2000 kilometer orbit. One part of the IVS, which contains the Orbiter, is separated, and the Orbiter is

A **Mars Sample Return** *spacecraft is launched back to Earth after a successful mission.*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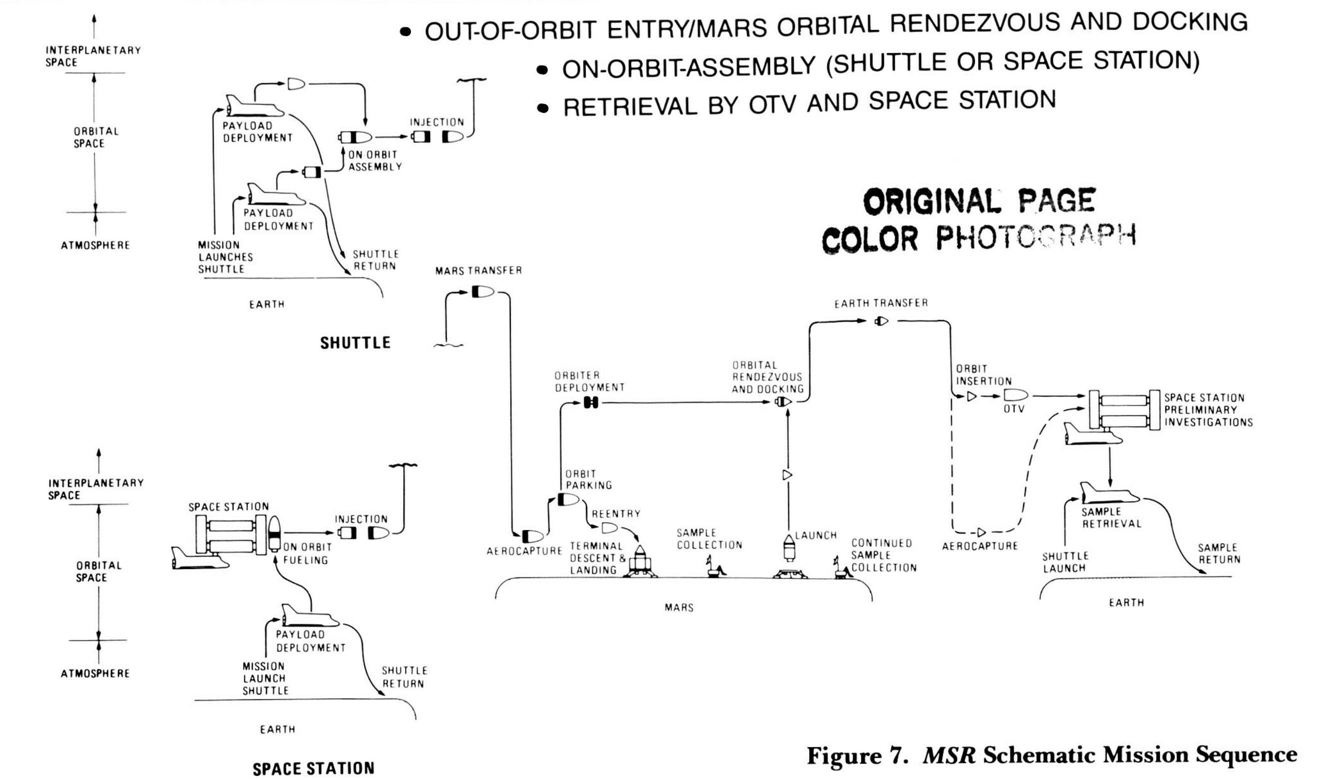
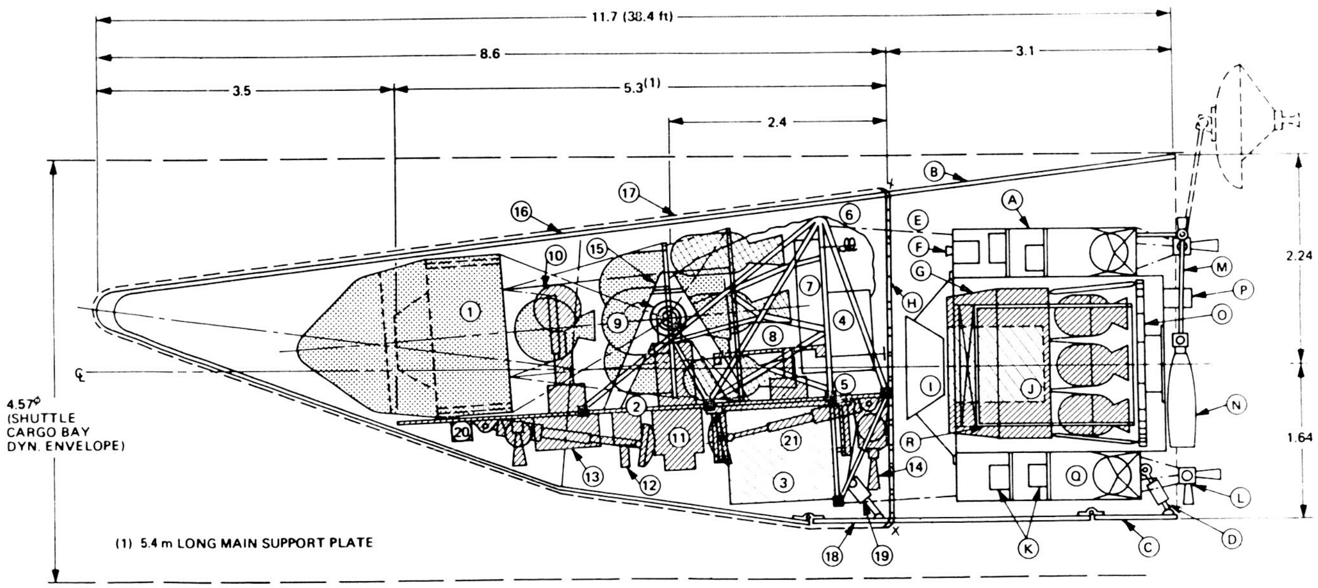


Figure 7. ***MSR*** **Schematic Mission Sequence**



LEGEND

1. MARS RENDEZVOUS VEHICLE (MRV)
2. MARS LANDER MODULE (MLM)
3. ROVER (STOWED)
4. PARACHUTE COMPARTMENT
5. AFT SUPPORT STRUCTURE (SEPARATES DURING VERT. PHASE AT POINTS MARKED "■")
6. VERT. PHASE PARACHUTE CABLE
7. MEC GUID. & RELAY RADIO EQUIP.
8. SCA TRANSFER DEV. & MAST
9. MRV ROTATION DRIVE/RELEASE MECH.
10. ANTENNA (HGA, LGA) & MAST
11. MRV ERECTION DRIVE
12. TERM. DESCENT RADAR
13. EQUIPMENT BOX
14. TERM. DESCENT ENGINE (5)
15. VERT. PHASE PARA. ATTACH./RELEASE
16. AEROSHELL
17. BIOSHIELD (SEPAR. AT "x-x")
18. FLAP (2)
19. FLAP ACTR. (2)
20. RTG
21. LANDG. LEG ASSY. (3)

- A. MARS ORBITER VEHICLE (MOV)
- B. MOV AEROSHELL
- C. FLAP (2)
- D. FLAP ACTUATOR (2)
- E. MEC-TO-MOV ADAPTER
- F. RENDZVS. GUID. LASER/IR DET.
- G. EARTH RET. VEHICLE (ERV)
- H. BIOSHIELD END CAP
- I. DOCKING CONE
- J. EARTH ORBIT CAPSULE (EOC)
- K. EQUIPMENT (TYP.)
- L. THRUSTER ASSY. (2)
- M. HGA BOOM
- N. HGA (+LGA)(FURLED)
- O. ERV SPIN TABLE
- P. ACS SENSORS
- Q. PROP. COMPTMT.
- R. SOLAR PNL. (2) (STOWED)

Figure 8. ***MSR*** **Interplanetary Vehicle System**

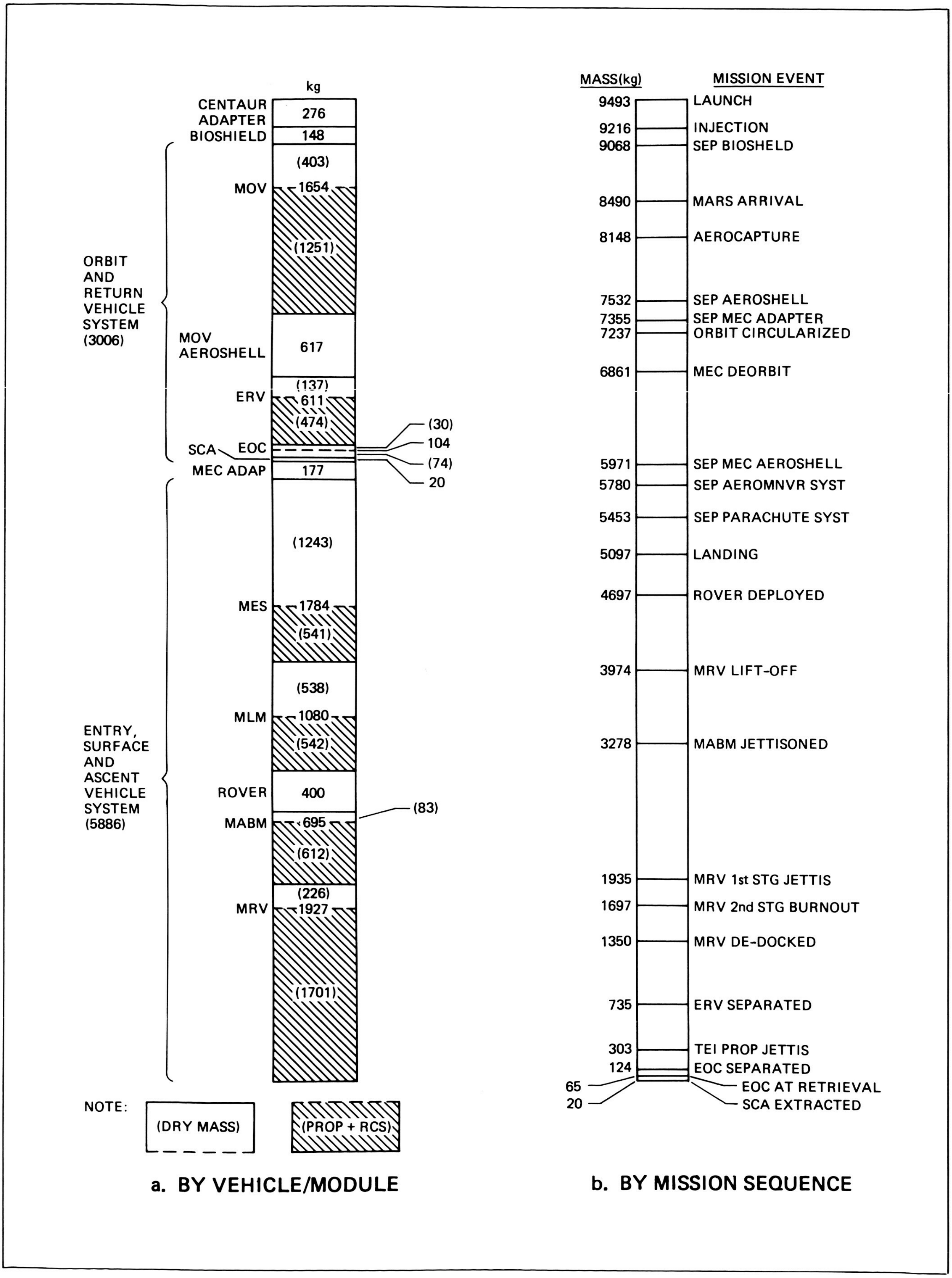
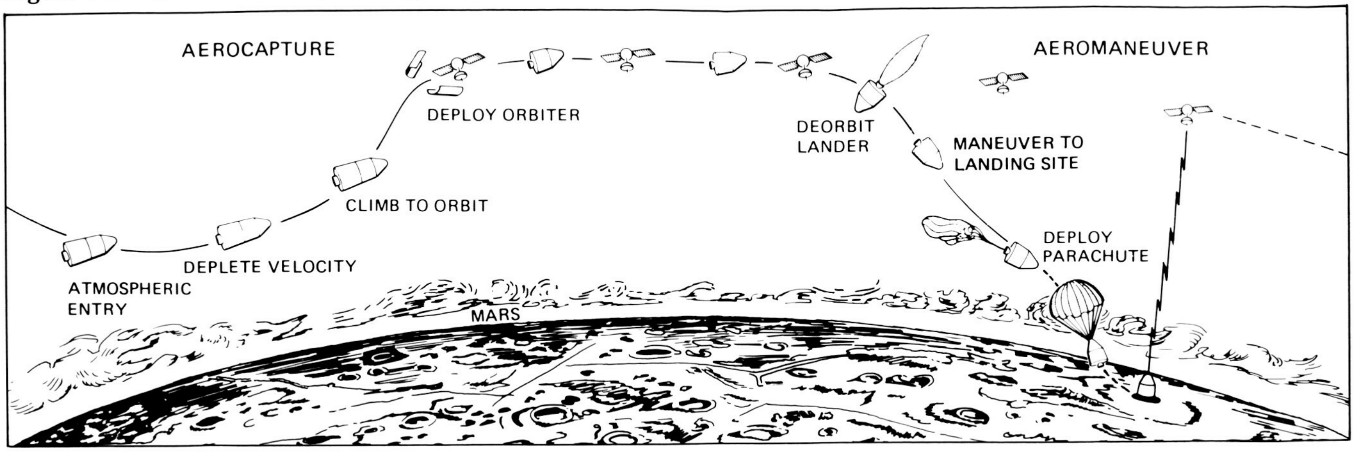


Figure 9. Baseline *MSR* Mission Mass Breakdown

Figure 10. Baseline Mission, Aerocapture/Aeromaneuver



deployed. The other part of the IVS, the Mars Entry Capsule, is then de-orbited to enter the Mars atmosphere, and it flies to the selected landing site by using aeromaneuvering techniques. Close to the landing site, a parachute and a terminal descent engine are used in the last phases of the landing trajectory. These aerocapture and aeromaneuvering operations are illustrated in Figure 10.

When the sample collection and surface operations are completed, the Mars Rendezvous Vehicle, which contains the samples, is launched from the surface of Mars into orbit to rendezvous with the Orbiter. These rendezvous maneuvers will be performed autonomously by the Orbiter, using tracking information obtained from rendezvous radar in the early, distant stages, and then carrying out the close approach and docking using infrared sensors which observe corner reflectors mounted in the Mars Rendezvous Vehicle.

After docking, the Sample Canister Assembly is transferred to the Earth Orbit Capsule, which is nested within the Earth Return Vehicle. The latter is then separated from the Orbiter and launched into an Earth return trajectory. At Earth, an aerocapture maneuver is used to place the Earth Return Capsule into a 12-hour orbit whose periapsis altitude is compatible with either the *Space Shuttle* or an OTV; the capsule is then recovered and either brought down to Earth or taken to the Space Station.

The Space Station could play an important role by making it possible to make preliminary analyses of the returned samples before they are brought down to Earth. Such a procedure would minimize any risk to the Earth environment, would reduce the risk of back-contamination of the samples, and would maximize the scientific value of the samples by providing data to help plan more complex long-term analyses.

In one possible procedure, a small portion of the sample would be sterilized on the Space Station and then returned to Earth for detailed examination; the remainder of the sample would remain in the Space Station until educated decisions can be made on the basis of the data obtained by analyses of the portion returned to Earth. Alternatively, a space quarantine facility, built as an essential part of the Space Station, could be used to evaluate the samples for biological activity and other potentially harmful effects before the samples actually enter Earth's biosphere. The major disadvantages of this second mode of operation are the increased cost and the greater complexity of the operation.

Whether the method of quarantine is Earth-based or space-based, it is clear that the Space Station and its associated space vehicles will enhance the possibility of making a safe recovery of the sample capsule as it returns to Earth. In addition, if the quarantine activity is conducted in space, the Space Station will provide a locus for the activity. If the quarantine operations are conducted on Earth, the Space Station will still be needed for recovering the sample capsule and for inspecting the capsule in order to insure safe transport in the *Space Shuttle* down to Earth's surface.

This baseline mission clearly meets the science requirements that are included in the working premises discussed earlier. The 400-kilogram Rover will make possible the "intelligent selection" of samples in the "near vicinity" of the Lander. Furthermore, if the Rover can be developed to include a high degree of autonomous operation, then the 401-day stay time on Mars may permit much longer Rover traverses.

Multiple Sample Return/Rover Missions

A single *Mars Sample Return* mission can stand alone on its own scientific merits, but such a mission can be enhanced–in ways both prudent and cost-effective–by nearly identical follow-on missions carried out in a short period of time after the initial landing. Two options are discussed briefly here. In the first option, the second landing is made in the same general area as the first, and the Rover from the first mission collects samples to be returned by the second. In the second option, the second landing is made elsewhere, and the mission operates independently.

In the first option, the Rover from the first mission would immediately sample the near-vicinity of its landing site and would place the samples in the ascent vehicle. The Rover would later augment this contingency sample with more carefully-selected samples which fully represent the key geologic units and rock types in the general area. When these two phases of sampling are complete, the ascent vehicle is launched to its orbital rendezvous, and the Rover begins a more extensive expedition.

So far, there is no change in the baseline mission. However, at this point, the baseline mission would be modified by having the Rover continue to collect samples on its extended traverse. A second mission could now land near the first Rover, retrieving the samples that it has collected. The result of this option would be that the samples collected during the extended traverse by the first Rover could be returned, together with additional samples collected at or near the site of the second landing.

The second option for multiple landings would reflect the decision to sample geologic regions that are too widely separated for the Rover to move from one to the other. Such a decision could reflect the high scientific priority for sampling widely-separated regions of Mars. In this case, the second mission would be a repeat of the first, the two Rovers would operate independently, and there would be no exchange of samples between the missions.

Mars Sample Return Mission: Candidate Landing Sites*

Site	Approximate Coordinates	One-Way Linear Roving Distance Required (km), Given Landing in Ellipse (km x km)		Sampling Objectives
North Pole A	86.5°N, 120°W	0	(50 × 80)	Perennial north polar ice
North Pole B	84.5°N, 105°W	30	(50 × 80)	Perennial north polar ice; soil from perennially ice-free trough
Arsia Mons West	8°S, 132.5°W	4.5	(50 × 80)	Young volcanic rocks
Apollinaris Patera Northwest	5°N, 190°W	6	(50 × 80)	Young volcanic rocks; eolian sediments
Chryse Planitia (VL-1 Site)	22.5°N, 47.9°W	2.5	(50 × 80)	Impact-crater ejecta; fluvial (outflow channel) sediments
Schiaparelli Basin Southwest	8°S, 336°W	18	(50 × 80)	Oldest martian crustal rocks from ancient, heavily cratered terrain
Tyrrhena Terra	7°S, 243°W	5	(5 × ?)	Oldest martian crustal rocks from ancient, heavily cratered terrain;
		5	(30 × ?)	Old volcanic rocks that mantle ancient crust
Iapygia	11°S, 278°W	5	(same as for Tyrrhena Terra)	
Candor Chasma	6.3°S, 73.8°W	5	(5 × ?)	Layered rocks from a canyon
Hebes Chasma	7°S, 77°W	5	(5 × ?)	Layered rocks from a canyon

* Abstracted from Mars Science Working Group Site Selection Team (1980) *Detailed Reports of the Mars Sample Return: Site Selection and Sample Acquisition Study*, Volumes I to X, JPL Report No. 715-23, Jet Propulsion Laboratory, Pasadena, California.

Additional Issues

Because this mission involves the return to Earth of martian material, together with spacecraft components that have been exposed to the environment of Mars, the general issues of planetary protection (including protection of Earth's biosphere) and back-contamination underlie many aspects of this mission.

On the one hand, it is necessary to protect Mars from contamination by terrestrial organisms. This concern makes it necessary to consider such problems as the sterilization of the spacecraft and its propellants, as well as the proper altitude for the Orbiter, in order to ensure an appropriately long decay time.

On the other hand, concerns also exist about the possibility of unplanned and uncontrolled introduction of martian material into the terrestrial environment. These concerns will affect the design of the sample collection and containment system. It will also be necessary to evaluate the potential for contaminating the Mars Ascent Vehicle, the Orbiter, and the Earth Return Vehicle with martian materials during the collection, recovery, and transfer of the samples. The related issues of quarantine and possible sterilization of the returned samples, and the protection of the samples from back-contamination by the terrestrial environment, remain to be resolved.

To resolve these questions will require extensive discussions in order to develop a consensus involving scientific, technical, and political planners. A *Mars Sample Return* mission marks the start of a new era of detailed planetary exploration, and the mission will require rethinking of the traditional planetary protection rules that have applied during the earlier stages of planetary Reconnaissance and Exploration, in which sample returns were not involved.

Summary

The collection and return of martian samples for analysis on Earth is the next essential step for raising our understanding of the Red Planet to a level from which meaningful interpretations can be made about the origin and evolution of all the terrestrial planets, including Earth. Such a mission will provide essential and otherwise unobtainable scientific information. It will also provide technical challenges in a number of areas that are essential to the further development of general space capabilities.

In the baseline mission described here, a total mission launch of about 9,500 kilograms, composed of seven vehicles and modules, will collect approximately five kilograms of martian samples with a 400-kilogram Rover and will return them to Earth in a 50-kilogram Sample Return Capsule. The Rover is essential for two purposes: to provide the mobility necessary to collect an adequate variety of materials in and around the landing site, and to characterize potential samples before the decision to collect them is made. The prime goal of the Rover is to collect contingency samples from within approximately 100 meters of the landing site. A secondary goal is to provide mobility of at least several kilometers, in order to make it possible to sample at greater distances. A third goal, to be undertaken only after the samples have been successfully delivered to the ascent vehicle, is to carry out an extended roving traverse, using its sample characterization capabilities to characterize the martian surface over distances as long as practical.

This mission depends heavily on space capabilities to be established during the 1990s. The mission requires the full capability of the *Centaur* launch stage, and this capability can be achieved either by on-orbit assembly or by on-orbit fueling. These capabilities, and other supporting functions, could be provided by the planned Space Station, although the Space Station is not necessary for the mission. The *Mars Sample Return* mission also involves: aerocapture at Mars for orbit insertion; aeromaneuvering and terminal guidance for entry and landing on Mars; semiautonomous operations on the martian surface; orbital rendezvous and docking at Mars for sample transfer; and aerocapture at Earth for orbital insertion and recovery of the Sample Return Capsule.

Even without the involvement of the Space Station, a *Mars Sample Return* mission presents a large number of important technical challenges in such areas as propulsion, manned orbital operations, spacecraft technology, aerocapture and aeromaneuvering, automated orbital rendezvous, autonomous sample collection and handling, and robotics. The mission will provide important extensions of our existing and planned capabilities in all these areas.

C-2

Is This a Piece of Mars?

When a sample of Mars is finally returned to Earth by an automated spacecraft, scientists may discover that, as in many other things, "Nature did it first." During the last few years, evidence has been gradually accumulating to suggest that eight strange meteorites, collected from places as far apart as India and the Antarctic ice cap, may have been blasted off Mars by giant meteorite impacts and hurled toward Earth millions of years ago.

These eight possible samples of Mars, some of which have been known for more than a century, are collectively known as SNC meteorites, from the names of towns where the first members of this group were found: Shergotty (India), Nakhla (Egypt), and Chassigny (France). The SNCs have always been considered unusual enough to be placed in a special group of meteorites. Most meteorites have a "primitive" chemical composition and are made up of small beadlike objects called chondrules. The SNCs resemble crystallized lava flows and have a chemical composition that suggests that they have gone through considerable chemical processing (*differentiation*), probably as the result of extensive volcanic activity on whatever world they came from.

During the last few years, more sophisticated geochemical tests have reinforced the unique character of the SNCs and have pointed toward Mars as the possible source. Minerals in the SNCs show a higher oxidation state than do other meteorites, and even hydrous (water-bearing) minerals are present. Textures of crystals in the meteorites indicate that they underwent complex melting and crystallization processes in a relatively high gravitational field. The ratios of oxygen isotopes in the SNCs are different from those in terrestrial rocks, lunar rocks, and other meteorites.

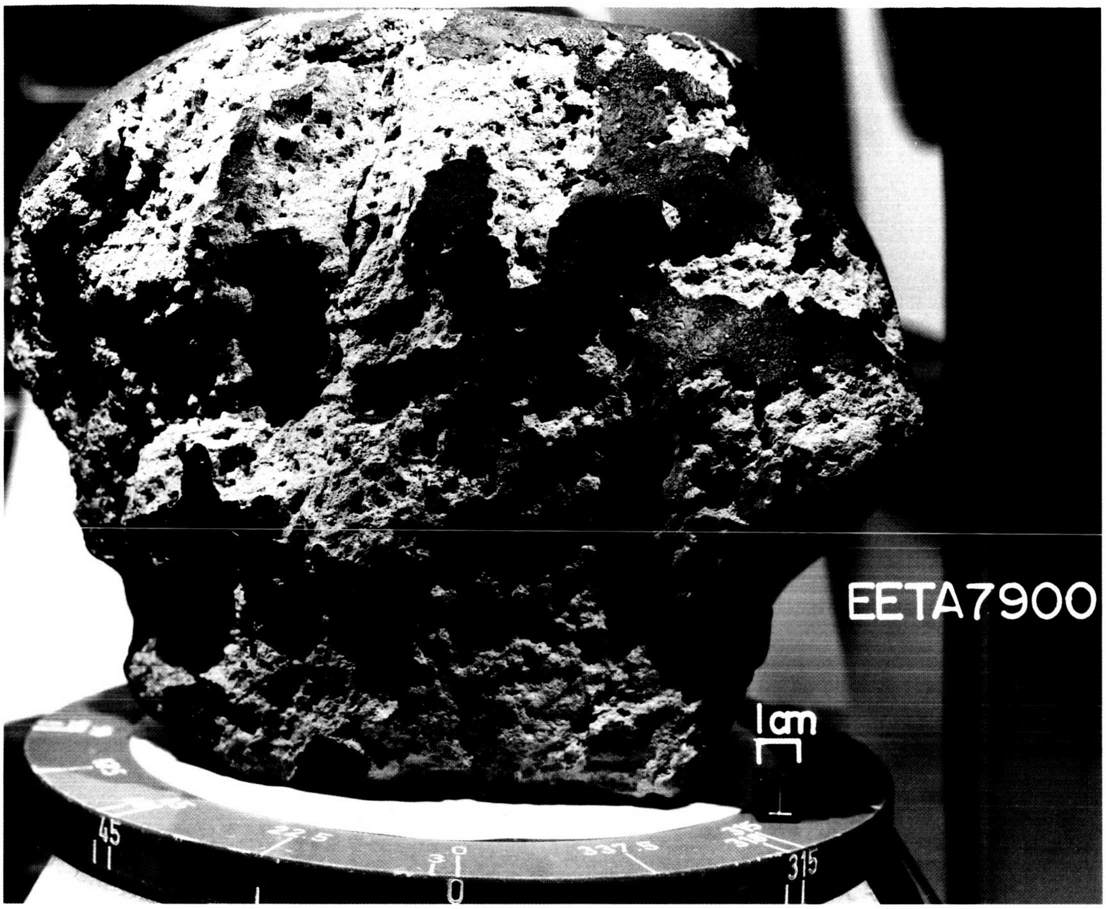
Ages measured on the SNCs provided some of the strongest evidence for their origin on another planet. Unlike most meteorites, which have ages of about 4.6 billion years, the time of formation of the solar system, the SNCs formed much later–about 1.3 billion years ago. This means that there must have been relatively young volcanic activity on their world, which in turn implies that their world must have been large enough to retain internal heat and to maintain volcanic activity for a long time after it formed. Asteroids, thought to be the parent bodies for meteorites, are too small. Even the Moon, which has had active volcanic activity, shows no eruptions younger than about 3 billion years old. A larger object is required, and Mars became an obvious candidate, especially after spacecraft pictures revealed geologically young volcanoes on its surface.

The unexpected discovery of two SNCs in a large collection of meteorites obtained from the Antarctic ice cap about six years ago spurred further work on this group and produced more evidence of a possible linkage with Mars. A key result was the discovery that gases trapped in the SNCs were totally different from gases found in other meteorites or in Earth's atmosphere and had chemical characteristics that closely resembled the measurements made by the *Viking* spacecraft on the martian atmosphere itself.

The notion that the SNC meteorites come from Mars solves some problems and raises others. Theorists have trouble explaining how a meteorite impact could blast a meteorite off Mars, through its atmosphere, and away from its high gravitational field (about one-third that of Earth). Current calculations also predict that any material ejected from such an impact would be completely melted, and no traces of the pre-impact crystal structure or chemistry would be preserved.

However, the impact idea has received some solid support from the discovery that several meteorites also collected in the Antarctic are unquestionably pieces of the Moon that were blasted off the Moon by impacts and hurled to Earth in the same way. The identification of these meteorites as lunar rocks is unquestionable–they are virtually identical to samples returned by the *Apollo* missions.

For the present, the SNCs will remain a tantalizing and frustrating group of specimens. Despite the evidence pointing toward Mars as the source, it will not be possible to be certain of their origin until samples of known martian material can be returned to Earth for analysis. (The unquestionable identification of the lunar meteorites was only possible because they could be directly compared with the large sample collections obtained by the *Apollo* missions.) In fact, determining the nature of the SNCs could be a most exciting result from a *Mars Sample Return*. If SNCs are not from Mars, then our theories of how meteorites formed need extensive revision. If they are from Mars, then we will have suddenly acquired eight more genuine martian samples that came from different places on Mars. We will, in fact, have obtained the results of *nine* sample return missions for the price of one.



SNC meteorite, discovered in the Antartic ice sheet, may have been blasted from the martian surface by a meteorite impact and hurled into an escape trajectory toward Earth.

Many of the technical issues related to a *Mars Sample Return* mission have not yet been well defined. Because of the importance of this mission, studies should be started as soon as possible to define in detail the technical developments required for the mission. Related studies should also be started to define the ways in which the capabilities of the Space Station can be used to support the mission and to enhance its performance.

Because of the scientific importance of a *Mars Sample Return* mission and because of the number and variety of technical requirements for the mission, **the SSEC recommends that studies be started at once to identify and develop the required technologies.**

The SSEC also recommends that studies be undertaken immediately to explore and define the capabilities of the Space Station to support the *Mars Sample Return* mission through such operations as on-orbit assembly, on-orbit fueling, spacecraft checkout, launch and recovery operations, and preliminary quarantine and examination of a returned sample.

A 1996-1998 *Mars Sample Return* mission can explore a new world and can return samples of that world to Earth. Like the *Apollo* landings on the Moon, this mission will be a benchmark in technological and scientific achievement. It will demonstrate the continuing leadership of the U.S. in space exploration, and it will lay an important foundation for the eventual manned exploration of Mars.

CONCLUSIONS

1. The nature of Mars, and its direct relevance to understanding Earth and the planets in general, make it a compelling target for in-depth exploration in the near future.

2. The return of unsterilized martian samples to Earth is the best and only way to make certain kinds of critical measurements that will determine: (a) the geologic history of martian rock units; (b) the evolution of the martian crust and mantle; (c) the interactions between the martian atmosphere and surface materials; (d) the presence of contemporary or fossil life.

3. The data base existing from previous Mars missions, including swaths of high-resolution imagery provided by the *Viking Orbiters*, is already adequate to plan and undertake a sample return mission. There is no need for a precursor orbiter mission or for orbital imaging associated with the sample return mission itself.

4. The Space Station is not necessary for a *Mars Sample Return* mission, but the capabilities of the Space Station can significantly enhance the mission. The Space Station can provide: (a) on-orbit assembly or on-orbit fueling of the *Centaur* launch stage; (b) enhanced capabilities for recovery of the Sample Return Vehicle in Earth orbit; (c) facilities for preliminary examination and/or quarantine of the returned sample.

5. Study of several different mission concepts indicates that the most advantageous options are those which involve: (a) aerocapture for initial Mars orbit insertion; (b) aeromaneuvering for atmospheric entry and landing; (c) post-sampling Mars orbital rendezvous between the Sample Return Capsule and the Earth Return Vehicle.

6. A considerable advantage can be achieved if it is possible to obtain propellants on the surface of Mars by *in situ* production from the atmosphere or soil. Such technology would probably not be appropriate for an initial sample return mission.

7. A *Mars Sample Return* mission provides major technical challenges in many different areas, including propulsion, manned orbital operations, spacecraft technology, aerocapture and aeromaneuvering, automated orbital rendezvous, autonomous sample collecting and handling, and robotics.

RECOMMENDATIONS

1. Because of the fundamental importance of Mars as a terrestrial planet (and as the only other potentially habitable planet in the solar system), the SSEC recommends that one thrust of the Augmented Program be Mars-oriented.

2. A *Mars Sample Return* mission should be carried out as soon as possible. Such a mission is the next essential step in raising our understanding of Mars to a level from which meaningful interpretations can be made about the origin and evolution of all terrestrial planets, including Earth.

3. A scientifically justifiable *Mars Sample Return* mission must provide a variety of rationally chosen samples from carefully selected areas. The highest-priority geologic units for sampling are: young volcanic units, intermediate-age volcanic units, ancient cratered units, layered sediment units, and polar cap units.

4. To maximize the scientific yield of a *Mars Sample Return* mission, a wide variety of martian materials must be sampled and returned to Earth: fresh igneous rock, weathered igneous rock, sedimentary (layered) rock, breccias, regolith, wind-blown dust, and possibly atmosphere.

5. To obtain a scientifically adequate suite of samples, a sample return mission must incorporate significant surface mobility, i.e., total traverse lengths on the order of tens of kilometers. A rover is therefore essential to the sample return mission in order to provide: (a) long-distance mobility; (b) imaging and instrumental characterization of the samples before collection.

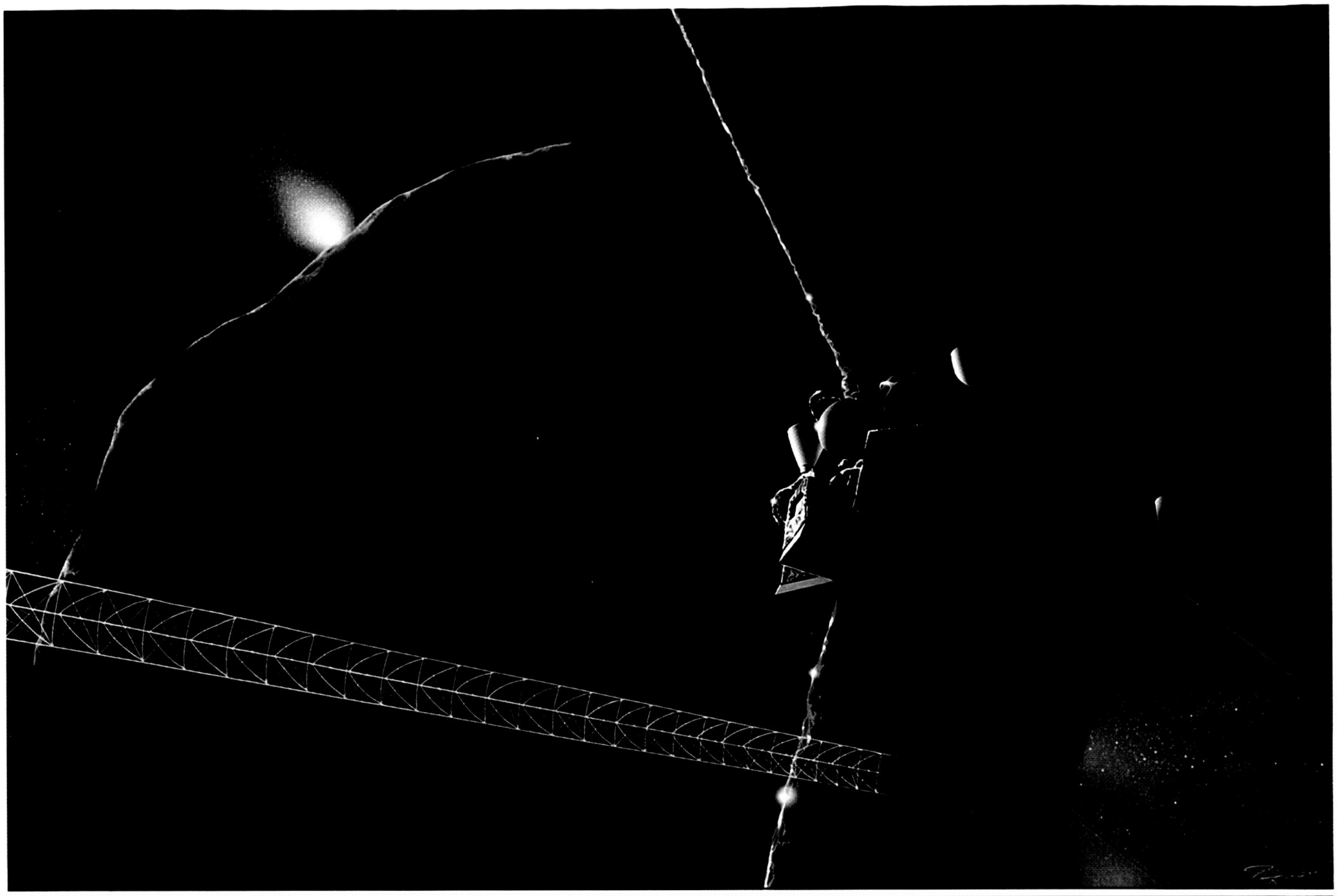
6. The prime purpose of a rover on a *Mars Sample Return* mission should be to collect a variety of materials within a radius of 100 meters from the landing site. A secondary goal is to collect more distant samples and return them to the spacecraft. A third goal is to carry out, after sampling is completed, one or more long-distance surface traverses.

7. To preserve critical geochemical and biological information potentially available in martian samples, sterilization of the samples by any method must be avoided.

8. Because the *Mars Sample Return* mission provides significant technological challenges, the identification, study, and development of required technologies should be undertaken as soon as possible in such critical areas as manned orbital operations, spacecraft technology, aerocapture and aeromaneuvering, automated orbital rendezvous, autonomous sample collecting and handling, and robotics.

9. Studies should be undertaken immediately to explore and define the ability of the planned Space Station to support the *Mars Sample Return* mission through such capabilities as on-orbit assembly, on-orbit fueling, spacecraft checkout, launch and recovery operations, and preliminary quarantine and examination of the returned sample.

After completing its on-orbit observations, a **Planetary Observer** *spacecraft prepares to land on a near-Earth asteroid.*



4. A Piece of Creation

A SAMPLE RETURN MISSION TO A COMET

What a Comet Can Tell Us

The small, chemically primitive objects of the solar system, comets and asteroids, are one of the most important frontiers remaining for future planetary exploration. In its 1980 report, *Strategy for the Exploration of Primitive Solar System Bodies*, the Committee on Planetary and Lunar Exploration (COMPLEX) of the National Academy of Sciences' Space Science Board (SSB) stated that investigations of these small objects:

"will provide understanding of a kind that is qualitatively distinct from that provided by studies of the planets and their satellites...As a group these objects provide an important link in our understanding of solar system evolution. This conclusion...reflects the general belief that many are composed of condensed material from the primitive solar nebula, which is either essentially unaltered or at least has not been altered to the extent of material on planetary and satellite surfaces."

COMPLEX therefore recommended that the primary goal of near-term investigations of small bodies should be:

"to determine their composition and structure and to decide their history in order to increase our knowledge of the chemical and isotopic composition and physical state of the primitive solar nebula and to further our understanding of the condensation, accretion, and evolutionary processes that occurred in various parts of the nebula before and during planet formation."

Comets are unique objects that have a special role to play in achieving these goals of understanding the origin and earliest history of the solar system. They appear to be mixtures of dust and ice that formed at low temperatures and have been preserved at low temperatures ever since. Their orbital and thermal histories are clearly different from all other solar system objects, including asteroids.

Although little is known about comets, it seems clear that they are small, ancient bodies that have resided at great distances from the Sun for most of the lifetime of the solar system. This distant region is the best place to preserve solar system materials for long periods of time. Solar heating is negligible; illumination levels are only a few microwatts per square meter. Furthermore, individual objects are widely dispersed, providing protection from collisions. These conditions produce a unique isolation ward where primordial materials, cryogenically stored, can remain unchanged for aeons.

Comets are therefore crucial to understanding the origin of planets for the simple reason that they are probably the best preserved relics of the early solar system. Even the asteroidal materials represented in meteorite collections have been modified to varying degrees by melting, collisions, heating, and even hydrothermal activity, from what they were originally.

Much of the scientific excitement surrounding a *Comet Nucleus Sample Return* mission arises from its potential to probe directly into the question of our own origins. Laboratory analyses of only a few kilograms of sample can produce precise and highly reliable data about the mineralogical, elemental, isotopic, and molecular compositions of both components of the comet nucleus–silicate dust and ice. This information will provide new insights into the origin and evolution of cometary materials and will enable us to attack a wide range of significant problems concerning the origin of the solar system and the relationship of the solar system to the rest of the universe.

Current hypotheses about the condensation and accretion processes that occurred in the earliest period of planet formation already predict that comets will exhibit certain patterns of trace element composition in their silicate materials as well as the presence of certain species of ices. These theories will evolve rapidly in the coming decade as the first spacecraft missions to comets provide new data. But even the newest theories can be tested definitely, and then refined or discarded, only when these cometary silicates and ices can be precisely analyzed on Earth in a well-preserved sample.

Such sample analyses will also provide critical information about the original sources of cometary material and about the genetic ties between comets and other astrophysical objects. Sample analyses can definitely establish, for the first time, the presence or absence in comets of interstellar grains, interstellar molecules, complex core-mantle grains, or possible biogenic elements and compounds. We can then make immediate comparisons between data from a returned comet sample and other data that are already available: astronomical observations of stars and interstellar clouds, laboratory analyses of meteorites and interplanetary dust particles, and the results of experiments that simulate astrophysical and cosmochemical processes. The comet sample data will fill a critical data gap that now prevents us from understanding the origin of comets and their relations to other objects, both inside and outside the solar system.

The timing of comet formation with respect to the rest of the solar system is another basic question which cannot be answered without returned sample analyses. Precise measurements of isotopic ages from several radioactive elements (both long-lived and extinct) in cometary materials (especially in the silicate dust grains) will enable us to place the formation history of comets into a more general astrophysical and solar system context.

Comets may have played a significant role in the origin and development of the terrestrial planets. It has been suggested that the original atmospheres of Earth and other planets may have obtained a significant amount of volatile materials from infalling comets. The measured molecular, elemental, and isotopic compositions of cometary materials will provide us with essential data to test this idea and to understand the evolution of planetary atmospheres.

Comets may even have played an essential role in the development of life. Such reactive molecular species as cyanides and aldehydes, if they existed in comets and survived atmospheric entry and impact on Earth, could have become a key part of the inventory of organic substances in Earth's early atmosphere and hydrosphere and could have had a profound influence on the chemical events that led to the origin and development of living systems.

The currently most popular theory for the origin of comets is that they formed as icy planetesimals in the vicinity of Uranus and Neptune and were gravitationally ejected to the outermost solar system. If this theory is correct, then collisions between comets–and the resulting alteration of the original material–are highly likely. Even so, cometary samples will still contain an invaluable record of early events that occurred in the very fringes of the solar system and perhaps even in the interstellar material that was present before the solar system formed. Observations of comets suggest that their volatiles are uniformly distributed inside them, implying that their interior materials have probably survived in pristine condition, without serious alteration.

Other possible theories, however, favor an origin for comets outside the solar system entirely, far beyond the orbit of Pluto. In these theories, comets may be frozen, unaltered samples of the

original interstellar matter from which the solar system formed. These materials might not even have been exposed to–or altered by–any of the environmental conditions where planets formed. Cometary material would then contain records of the origin and evolution of interstellar grains–and planetary sciences and astrophysics would find another common ground.

We already know that many other stars lose large amounts of mass in the form of tiny grains that are expelled into interstellar space by a variety of mechanisms which range from strong stellar winds to supernova explosions. We also know that such interstellar grains survive for a long time in our Galaxy, and they could have been incorporated into newly-formed comets. By detecting and analyzing interstellar grains in cometary materials, we can obtain new chemical, isotopic, and physical clues to the formation of the chemical elements in the Galaxy and the origin of the grains ejected from a large number of stars.

Why Collect a Comet?

COMPLEX gave the highest priority to the objective of determining the composition and physical state of the cometary nucleus. **The SSEC strongly concurs with this priority.** In fact, the importance of studying a comet nucleus in detail was the basis for recommending a comet rendezvous mission in the Core Program.

The SSEC also considers that no mission short of a *Comet Nucleus Sample Return* can provide the range and detail of analyses needed to definitely characterize the composition and structure of comet nucleus material. Remote sensing and dust collection techniques, which will be used on the rendezvous mission, can only sample material derived from the surface and the outermost skin of the comet's nucleus. This surface material has almost certainly undergone heating, outgassing, radiation exposure, and other processes that have altered the nucleus material from its initial state, especially if the comet has made many close approaches to the Sun. Furthermore, remote sensing techniques on a rendezvous mission are inevitably restricted in that only certain types of measurements can be made with the required precision using spacecraft instrumentation.

Some data about the unaltered nucleus could be obtained from instruments carried on a penetrator, which could be fired into the nucleus from a spacecraft in rendezvous with the comet. (Such an option is being considered for the *Comet Rendezvous/Asteroid Flyby (CRAF)* mission in the Core Program.) However, the capabilities of penetrator instruments are severely limited by constraints of size, weight, and power, and their data will not be extensive enough or precise enough to attack many key problems. Furthermore, these instruments cannot provide essential data about such critical properties of the comet nucleus as mineral composition, crystal structure, and fabric.

The crucial importance of obtaining and returning to Earth a sample from a cometary nucleus, collected from below the outer zone of alteration, is that the least altered material from a comet

Comets: The Quest for Stardust

Comets may contain clues to more than the origin and history of our own solar system. Comets may actually tell us–just as a few rare meteorites have already done–about the nature of interstellar space and the behavior of nearby stars when the solar system formed.

Comets contain two anticipated records of activity beyond the solar system: dust particles, and atomic isotopes. The existence of large amounts of dust between the stars has long been known from telescopic observations. If comets formed in the outermost parts of the solar system, is their dust like the dust we see near the Sun, or does it resemble the dust that lies further out, between the stars? Careful comparative studies of the dust collected from a comet should tell us whether comets are strictly local or whether we can use them as probes of interstellar space.

The ratios of *isotopes* (atoms of the same element with different atomic weights) in comet materials will also provide an important clue concerning possible interstellar characteristics. These isotope ratios provide the chemical signature for the material out of which comets and other solar system objects formed. Analyses of terrestrial rocks, meteorites, and lunar samples all point to a single conclusion: that the solar system was a well-mixed chemical system in which the isotopic ratios were originally uniform.

But during the last few years, some rare meteorites have proved to have different ratios from the rest. Analyses of these meteorites indicate that a single isotope (such as oxygen-17, hydrogen-2, or neon-22) was somehow quickly added to the solar system material just before the meteorite formed. Such a sudden and unique addition requires a special mechanism, and the best explanation suggested is that material from a nearby star was suddenly injected into the original solar system. The neon-22 and hydrogen-2 (also called deuterium) may have come from a red giant, while the oxygen-17 may have been produced by an exploding supernova. More than a dozen such isotopic anomalies have now been detected, and each new discovery is providing hard evidence about the behavior of stars in our solar neighborhood.

Among the hundreds of measurements that will be made on samples of returned cometary material, measurements of key isotopic ratios have a high priority. Will comets turn out to be part of the well-mixed original solar system? Or, having formed much further out from the Sun, will they contain an ever greater and more readable record of the stars beyond?

Earth-based view of Halley's Comet, taken before perihelion on January 17, 1986, from the University of Arizona's Lunar and Planetary Laboratory.

Comets and Life: Building Blocks or Microbes?

One of the major reasons for analyzing a comet in detail is to determine what role comets may have played in the origin of life on Earth. Did life arise on Earth independently, or did comets play an essential role by bringing in the essential biological building blocks to Earth?

The basic atoms necessary for life–carbon, hydrogen, oxygen, nitrogen, sulfur, and phosphorus–have all been present since the beginning of the solar system. Organic compounds–ones based on carbon and necessary for life–are widely distributed. Everywhere we look–on Earth, in meteorites, in the atmospheres of Jupiter and Titan, even in the nearly empty reaches of interstellar space–we find organic molecules. The outstanding question is how these compounds came together to produce life.

If comets are (as we think) original preserved relics from the formation of the solar system, then they may hold essential clues about the development of organic materials and life on our own planet. Do comets contain organic materials? What kinds? Did Earth have an original inventory of organic materials or were they brought in by the impacts of comets? Could the impacts of comets have produced our atmosphere and made Earth suitable for life? Until we can determine what comets are really made of, we have no way of answering these questions.

It seems likely that we will find organic compounds in comets, even as we have already found them in primitive carbonaceous meteorites. Observations of comets lend some support to this idea; comet nuclei, especially that of Halley's Comet, seem to be dark and reddish, a hue best explained by carbonaceous organic materials much like those found in meteorites. At least one scientist, Fred Hoyle, has argued that comets contain even more–actual microbes that have been left on Earth by passing comets to cause epidemics of flu and related diseases.

Few scientists go so far as to agree with Hoyle's ideas, but no one doubts that studying the organic material in a comet is an essential task if we are to unravel how terrestrial life–and the pleasant environment that supports it–came into being. By bringing a piece of a comet to Earth in the future, we can understand how our planet–and perhaps ourselves–has been shaped by pieces of comets that came to Earth in the past.

can then be subjected to the entire range of laboratory capabilities available on Earth at the time of sample return, as well as to new analytical techniques as they are perfected.

It is now within the reach of foreseeable technology to collect pristine samples directly from the nucleus of an active comet and to return them to Earth for intensive laboratory study. Such an undertaking can make possible, for the first time, in-depth studies of the environments and processes that existed during and possibly before the formation of the solar system. Current missions (*Giotto*, *VEGA*, and *Planet-A* to Halley's Comet), together with the *CRAF* mission recommended for the Core Program, will provide vital information about the nature of comets and their behavior in the inner solar system. Despite these eagerly awaited achievements, the ultimate scientific treasure of comets–the information frozen into their solid constituents–will remain untouched. To obtain this treasure, we must obtain and return samples of the nucleus to Earth.

How to Analyze a Comet

The value of laboratory sample analyses in addressing major problems of solar system science has been amply demonstrated by extensive studies of meteorites and lunar samples. These studies have succeeded in establishing the general properties and evolutionary histories of both the Moon and meteorite parent bodies. Similar studies of cometary material will unquestionably produce a similar revolution in our understanding of the early solar system.

Despite our limited study of comets thus far, we can already predict some of the general characteristics of cometary material. Certain meteors entering the atmosphere are apparently derived from comets. These materials seem to be fine-grained and porous, and their chemical composition is like that of primitive *(chondritic)* meteorites. Some of the silicate fraction of these meteors survives atmospheric entry and is collected as dust particles in the upper atmosphere. These small, fluffy particles are composed of even smaller crystals of meteoritic minerals–such as olivine, pyroxene, and iron-nickel metal. If we are correct in thinking that these particles come from comets, then we expect that similar silicate material will be found in a comet, mixed in some way with ices composed of several volatile species–possibly water, ammonia, methane, or more complex compounds.

A sample from a comet nucleus, collected from below the zone in which the surface is altered by heat and radiation, will probably be a representative sample of the whole body. The sample will probably consist of a mixture of ices and silicate dust. However, the ice-dust mixture may be so fine-grained that most of the information is locked up in individual particles much less than a millimeter in size. For such fine-grained material, the value of *in situ* analyses made by a spacecraft is limited. A major advantage of a returned sample is that the material can be processed, manipulated, and separated in great detail in the laboratory environment. Furthermore, laboratory

measurements provide the ultimate in resolution, precision, and sensitivity. Moreover, because many of the analyses are nondestructive, the results of the mission are not limited to any current state of the art; unconsumed material remains a resource that can be studied indefinitely with new techniques.

When the comet sample is brought to Earth, it will be subjected to an intensive set of studies by a global community of scientists. Using our experience on meteorites and lunar samples, sequential analyses of the sample will be organized to maximize the science return and to minimize sample damage and consumption.

From our experience with lunar rocks and meteorites, we can already anticipate how the non-ice solids of a comet (silicate minerals and metal grains) will be analyzed. A first-look examination will determine whether the material resembles any known meteoritic material. Such a preliminary examination will also include measurements of the chemistry, mineral composition, crystal structure, and textural fabric, using techniques already established for lunar samples and meteorites.

However, new techniques will need to be developed to analyze cometary ice in the solid state. Such analyses may be complicated by intimate mixing of dust and various types of ice on a fine scale. If the ice is not too unstable, a large range of microtechniques can be used: electron microscopy, electron surface scanning analysis (ESCA), Fourier-transform infrared spectroscopy (FTIR), energy-loss spectroscopy, and laser probe analysis.

Some of the earliest studies on a returned comet sample will involve the search for clues as to whether the small particles in the sample formed in the solar nebula, or earlier yet in the interstellar medium. One especially exciting approach to this question will be to look for special isotopic effects, already detected in meteorites, that indicate the presence of pre-solar materials: for example, "Neon E" (pure neon-22), high deuterium/hydrogen ratios, effects of primordial aluminum-26, and anomalous oxygen isotopic compositions. Many such anomalies have already been found in meteorites; the anomalies apparently reflect isotopic effects that predate the origin of the solar system.

Unfortunately, these effects have been diluted or obscured by subsequent processes that occurred in the solar system. The great promise of comets is that they may provide pre-solar materials that have survived totally intact and undiluted. In such materials the special isotopic effects should be dramatic, and their interpretation will accordingly be much more straightforward.

In addition to the search for pre-solar material, cometary samples will be studied with a wide range of techniques to determine their age, thermal and radiation histories, and possible alteration effects since they were formed. From such studies, we should be able to establish the relatively limited evolution of cometary nuclei during their aeons in the deep-freeze environment of the outer solar system.

Did Comets Kill the Dinosaurs?

Comets have long been associated in the human mind with disasters. (In fact, the word *disaster* literally means "bad star.") Past appearances of comets have been linked to many major events in human history–wars, invasions, the destruction of cities, and the deaths of kings. Now, scientific studies are beginning to suggest that comets can produce their own disasters on Earth–not merely by appearing in the sky, but by striking Earth itself.

For several decades, a comet has been considered as a likely culprit behind the great explosion that shook Siberia–and literally echoed around the world–on June 30, 1908. The energy of the explosion–more than 12 million tons of TNT–produced small earthquakes almost 1,000 kilometers away, sent atmospheric pressure waves twice around the world, and felled trees over an area of several hundred square miles. Twenty years later, investigators finally penetrated to the site of the blast and found great devastation, but no crater and no meteorites. This strange event has given rise to many fanciful explanations–a black hole, a chunk of antimatter, or even a runaway spaceship. However, a comet, made of a fragile mixture of dust and ice, seems the best possibility. Such an object would disintegrate in the atmosphere, producing a tremendous release of energy, and leave no recognizable solid material behind.

More recently, some scientists have argued that periodic showers of comets, bombarding Earth every 26 million years, have been responsible for the major extinctions of life that have been found at various places in the geologic record. Although this idea is still speculative, there is strong evidence that *something* struck Earth at the time of one of these extinctions, the so-called Terminal Cretaceous Event, which occurred 65 million years ago.

The Terminal Cretaceous Event was a major extinction by anyone's standards. About 75 percent of the known species disappeared at this time. Especially devastated were two groups of creatures at the large and small ends of the size spectrum–tiny marine one-celled animals, and the huge land reptiles *(dinosaurs)* that had ruled the land for more than 100 million years. The dinosaurs were utterly wiped out, and theories about what killed them have enlivened scientific debates during most of the past century.

Now there is hard evidence that the extinction was caused by an extraterrestrial body striking Earth. At more than 75 sites where the boundary between Cretaceous rocks and the younger Tertiary rocks is preserved, the thin layer of clay that separates them is greatly enriched in the element *iridium,* a metal that is rare in Earth's surface rocks but more common in meteorites. The same rocks also contain grains of quartz, a common terrestrial mineral, that have been deformed by intense shock waves like those generated by known meteorite impact events.

Despite the evidence for an extraterrestrial impact at this time, there is still controversy about how (or even whether) the impact could have caused the mass extinction. One possibility is that the impact threw up so much dust into the stratosphere that the sunlight was blocked out, most plants died, and the food chain collapsed. Another suggestion is that the impact produced enough energy to heat the atmosphere (or the oceans) by several degrees, enough to kill many of the inhabitants. There is also strong evidence (in the form of extensive carbon deposits at the Cretaceous-Tertiary boundary) that the heat of the impact caused a continental-scale fire storm that would have had devastating effects on life.

Even the scientists who agree that some kind of extraterrestrial impact took place at the end of the Cretaceous period differ on what the incoming object was. Some argue that it was an Earth-crossing asteroid, like the objects thought to have created many of the ancient meteorite craters that have already been recognized on Earth. Others argue that it was a comet. Still others have combined the idea of extraterrestrial impacts with the apparently periodic character of observed mass extinctions to form a more sweeping theory. They suggest that every 26 million years the great cloud of comets surrounding the solar system is somehow perturbed, sending showers of comets into the inner solar system to bombard Earth and the other planets. As a result, every 26 million years or so, most of the life on Earth is destroyed and new forms arise to take the places of the old ones. There is also debate as to just what this unseen perturbing object is: one theory proposes an unseen stellar companion of the Sun, appropriately called "Nemesis"; another suggests that it is an unseen tenth planet, "Planet X."

The possible ties between comets, mass extinctions, and the evolution of life on Earth

have been one of the most exciting recent developments in study during the past few years, and the discoveries and controversies show no sign of slackening off. No matter what theories are finally proven or disproven, the new discoveries, and the controversy they have generated, have been valuable. Regardless of whether extinctions are, in fact, periodic, regardless of whether Nemesis exists or not, regardless of whether dinosaurs were killed by the impact or just happened to die out just before the object struck, the discovery and debate have been stimulating. Large numbers of scientists have been forced to look outside the narrow limits of their own specialties, to develop new ideas, and to realize that Earth can be affected and changed by forces from beyond it.

A cometary or asteroidal impact may have caused the demise of the dinosaurs 65 million years ago.

Scientific Objectives for a *Comet Nucleus Sample Return* Mission

The basic scientific objectives for a *Comet Nucleus Sample Return* mission, and for the subsequent study of the returned samples on Earth, have been developed by COMPLEX and by several additional science working groups over the last few years.

1. ***Determine complete elemental and molecular composition.***

- Compare with compositions of the Sun and meteorites in order to understand condensation and accretion processes in the early solar system.
- Compare with compositions of planetary atmospheres in order to evaluate the role of comets in the formation of the original atmospheres of Earth and the other planets.
- Establish composition of the source materials for the cometary coma, thus improving our understanding of the interaction of comets with the space environment and thus making possible better interpretations of remotely-observed spectra of other comets.
- Compare with interstellar molecules to establish possible genetic relations.
- Identify and study abiologically synthesized organic molecules from a new solar system source, in order to evaluate the significance of comets as sources for organic materials to Earth and the other planets.

2. ***Determine isotopic composition of key chemical elements.***

- Establish an absolute time scale for cometary events: formation of silicate grains, formation of comets, subsequent alteration of comets.
- Establish initial isotopic compositions of cometary material, and compare with similar data for interstellar matter and other stars.

3. ***Determine mineralogical composition.***

- Establish relationships of material in comets to other planetary materials, e.g., interplanetary dust and meteorites.
- Determine physical and chemical conditions during formation and subsequent alteration of cometary materials.

4. ***Determine physical properties of the nucleus.***

- Measure bulk density of nucleus and the strength, optical properties, and structure of icy and silicate material making up the nucleus.
- Establish how silicates and ices are mixed together in the nucleus in order to understand formation and alteration processes in the comet.
- Obtain basic data to understand comet outgassing mechanisms and the formation of secondary deposits and other surface features.

The European space probe,* Giotto, *encounters Halley's Comet in March, 1986. The nucleus of Halley's Comet is in the center of the image (left) taken from a distance of 20,000 kilometers. Multicolor image (right), taken from 18,000 kilometers, reveals the irregularly shaped nucleus.

For the volatile materials in the comet sample, the main questions involve how and where these low-temperature condensates were formed and introduced into the comet. Were they frozen under equilibrium conditions, or were they trapped by nonequilibrium processes like catalysis, chemisorption, or irradiation?

To determine whether the volatile materials in comets played a major role in forming planetary atmospheres, analyses will be made to identify possible "tracer" chemical elements in the cometary sample and to compare them with similar elements in planetary atmospheres. The molecular and isotopic composition of the cometary volatiles will also be precisely determined. Initial measurements will probably involve analyses of the gases released during gradual heating experiments–an approach that has been successful in analyzing meteorite samples.

Concept for a Comet Sample Return Mission

The *Comet Nucleus Sample Return* mission is at an earlier stage of definition and design than the *Mars Sample Return* mission, chiefly because we have not yet learned as much about comets as we have about Mars. Current plans for this mission must therefore rely almost entirely on theoretical models for comets and on Earth-based and Earth-orbital observations.

Fortunately, the existing data base on comets is beginning to expand as a result of the recent flyby of Comet Giacobini-Zinner (G-Z) by the *International Cometary Explorer (ICE)* spacecraft on September 11, 1985. A major increase in information has come from the multiple spacecraft flybys and extensive Earth-based observations of Comet Halley in March-April, 1986. Furthermore, the *Comet Rendezvous/Asteroid Flyby (CRAF)* mission, being studied for the early 1990s, will provide essential long-term observations of a third comet. This mission will make the first detailed, long-term characterization of a comet nucleus, and it may even implant a penetrator in the comet's nucleus to make *in situ* analyses of the nucleus material.

The spacecraft data, especially the results of the *CRAF* mission, will allow us to accomplish several essential tasks: to observe a comet nucleus at close range, to determine the nature of its surface, to characterize the dynamic activity of the comet near the Sun, and to evaluate the hazards to a spacecraft near a comet.

A brief study of a possible *Comet Nucleus Sample Return* mission has been carried out; the results are described below. Because the present data base is still limited, the concept for this mission is necessarily general and vague on some critical details. However, the discussion does provide a fairly complete description of the principal aspects of the mission and allows the required technology developments to be identified.

The *Comet Nucleus Sample Return* mission will be launched into Earth orbit by the *Space Shuttle.* Because of the weight of the spacecraft system and the requirements for rendezvous with the comet, **the mission needs more propulsive capability out of Earth orbit than can be provided by any currently available launch stage,**

What Do We Get from a "Dirty Snowball"?

The current model for comets, which has now survived for several decades, was proposed by astronomer Fred Whipple in the 1950s. In his view, the nucleus of a comet is a "dirty snowball," a mixture of ices and silicate dust. Unromantic as this may sound, these two materials–dust and ice–were probably the basic ingredients of the solar system, and they were assembled, in varying amounts, to form all the planets and moons, from iron-rich Mercury to the icy satellites of Uranus.

The solid stuff in a comet nucleus is therefore an essential material for understanding the origin and history of the whole solar system. With samples of a comet in our hands–and in our laboratories–we can:

- Study in detail an unaltered sample of the *oldest preserved solar system material.*
- Determine the *chemical and isotopic character* of primordial solar system material (both dust and ices), especially the material that existed in the outer parts of the solar system.
- Determine the presence and nature of *carbon and organic molecules,* which are important for understanding the origin of life in the universe.
- Make chemical and mineralogical studies of *cometary dust particles,* in order to determine how they are related to meteorites, interplanetary dust, and interstellar dust.
- Detect possible *trapped interstellar materials* in comets.
- Determine the *history of a comet:* when it formed, how and when it may have changed, and whether it contains material from before the solar system formed.
- Determine the *surface alteration of the comet* as a result of repeated solar heating, radiation from the space environment, and other effects.
- Detect possible *trapped solar-wind and cosmic-ray particles,* making it possible to use the comet as a probe for exploring the history of solar and cosmic-ray activity in the solar system.

including the *Centaur*. Accordingly, the development of some type of low-thrust propulsion system (such as solar-electric propulsion) is considered essential to carry out the mission with a single *Shuttle/Centaur* launch.

Once the spacecraft is deployed in Earth orbit, the low-thrust propulsion system will be fired to propel it out of orbit and place it in the trajectory required to intercept the target comet. As the spacecraft nears the comet, it will be turned around so that the thrust from the propulsion system will slow the spacecraft and place it in rendezvous with the comet.

The initial rendezvous will be at a relatively great distance from the comet, in order to obtain an overall view and to evaluate any dangers associated with closer approach. Subsequently, the spacecraft will approach the comet for a closer inspection, including

measurement of the rotation rate of the nucleus. Based on our current knowledge of comets, a rotation period of ten to 15 hours is expected. (More detailed measurements for a specific comet will be made by the CRAF mission.) During this close approach, the sampling sites will be selected and the sample-collection operations themselves will be carried out.

The spacecraft system consists of a spacecraft bus, two sampling devices, an Earth return capsule, and a long-lived surface lander. The spacecraft bus will provide round-trip interplanetary transportation for all the other system elements, except for the long-lived lander, which will be left on the comet's surface. The spacecraft bus will carry a scientific payload to characterize the comet nucleus and to document the sampling site prior to sampling. The bus also will provide relay control and communication during the sampling process.

The unique nature of cometary material, and the crucial importance of the information it contains, impose some critical constraints upon both the mission and the sample collection operations:

- **A sample from beneath the surface of the comet nucleus is essential to provide preserved primordial material that has not been altered by surface processes**. A core sample about one meter long, drilled from the surface of the nucleus, should penetrate the altered surface layer and should reach the pristine material underneath. Such a core sample will also provide the near-surface stratigraphy that is a direct record of the history of the cometary nucleus–the effects of repeated solar heating, radiation bombardment, and other processes in the space environment.

- **Low-temperature preservation of the sample from the time of collection is essential**. Specifically, we must preserve in the sample the original inventory of thermally sensitive organic and volatile components, the original structures and textures of ices, and the intergrowths and associations between volatile and non-volatile components. We will thereby be able to determine the extent to which secondary processes have affected the chemical and physical characteristics of the nucleus materials during the comet's accretion and subsequent history.

Two separate sampling devices will be deployed from the spacecraft to land on the comet. The collection of two separate samples, each a core one meter long by six centimeters in diameter, is planned in order to enhance the reliability of the sampling process and to provide an opportunity to sample different parts of the comet's nucleus. One sampler will carry with it the long-lived lander that will be anchored to the comet's surface upon impact. This lander will make *in situ* characterizations of the sampling site and will monitor the surface activity on the nucleus for as long as possible after sample collection.

After collection of the samples, the sampling devices will lift from the comet, to be recovered by the spacecraft, using automated rendezvous and docking techniques. After recovery, the core samples will be sealed in an environmentally controlled capsule to

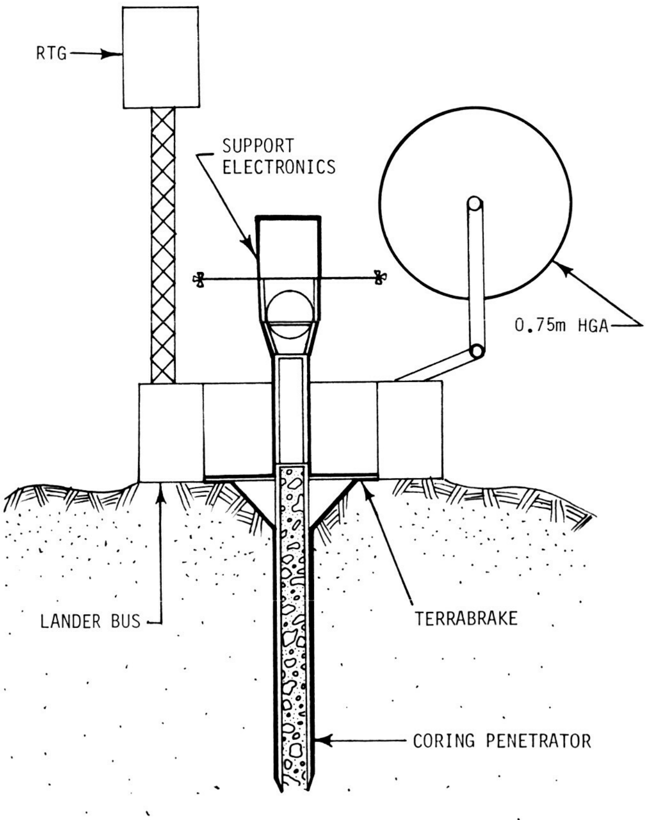
Comet Nucleus Sample Return Spacecraft System

The spacecraft system for the *Comet Nucleus Sample Return* mission consists of several different components.

- *Spacecraft bus.* This part of the spacecraft provides round-trip travel from Earth to the comet and back, including the maneuvers necessary to rendezvous with the comet and to approach it closely enough to launch the samplers. The spacecraft bus carries instruments to make remote scientific studies of the nucleus before sample collection, and it provides the communication and relay control for the sampling operations themselves.
- *Deployable remote sampling devices.* These two devices are launched from the spacecraft to land on the comet and collect the samples. They must be capable of landing on the surface and of anchoring themselves securely to the icy crust. Each sample contains a drill capable of penetrating into the nucleus and collecting a one-meter core sample. After collection, the samplers must launch from the comet's surface and rendezvous successfully with the spacecraft bus.
- *Earth return capsule.* The samples returned from the comet to the spacecraft bus are immediately transferred into this sealed capsule. The capsule must provide the contamination-free, low-temperature environment required to preserve the collected cores in their original state during the return to Earth. The capsule is equipped with retro motors, which are needed to change the Earth-approach trajectory into a circular orbit which can be reached by the Space Shuttle.
- *Long-lived surface lander.* This device is landed on the comet's nucleus with one of the samplers and is left there when the samples are returned to Earth. The lander is a long-lived instrument station that monitors the surface activity of the comet's nucleus through one complete orbit of the comet and will transmit its observations to Earth.

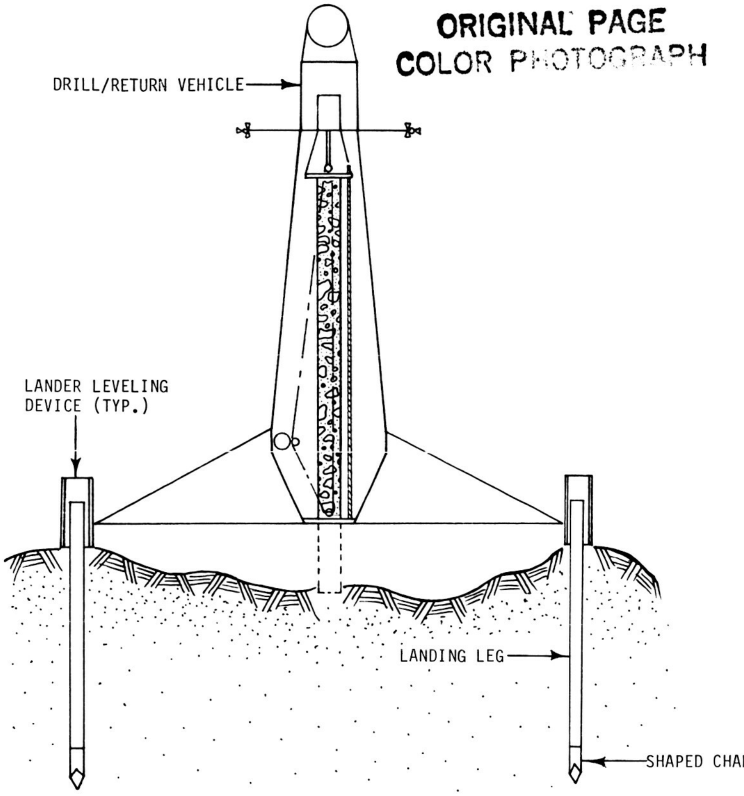
The most complex parts of the spacecraft system are the deployable remote sampling devices and the long-lived surface lander. Several different preliminary design concepts for these items are shown here.

PENETRATOR SAMPLER/LANDER



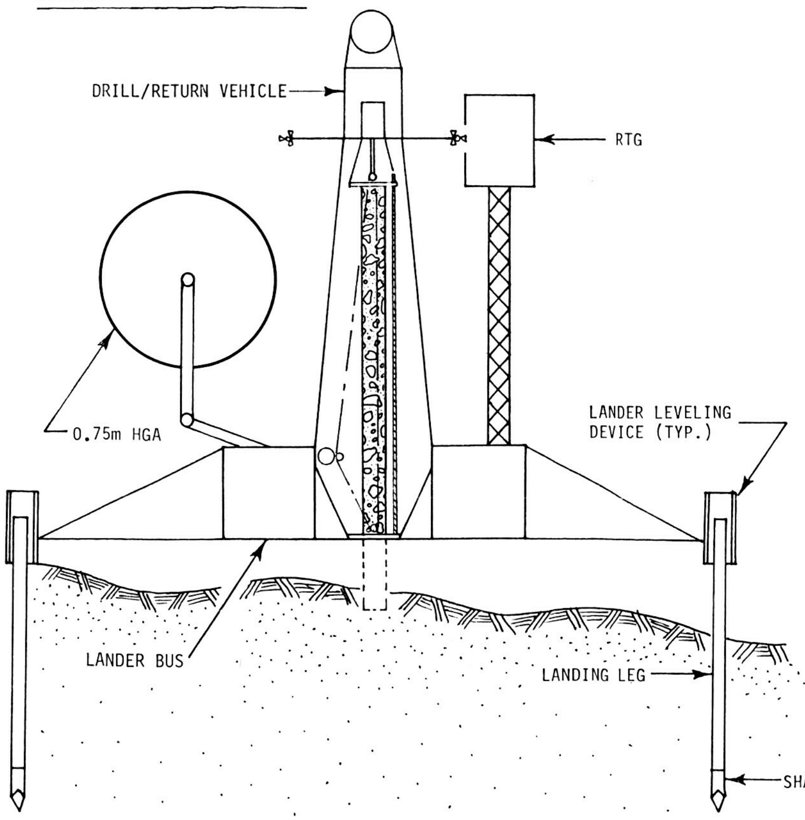
		SAMPLER		LANDER
SCIENCE		1.0		10.0
COMMAND/DATA HANDLING		2.0		16.0
TELECOMMUNICATION		1.2		11.2
AACS		1.6		0
REACTION CONTROL SYSTEM		2.4		0
POWER/PYRO		1.9		13.5
STRUCTURE		6.2		46.2
THERMAL CONTROL		0.6		9.0
CABLING		0.3		5.0
DEVICES		1.2		8.0
SUBTOTAL		18.4		118.9
CONTINGENCY	(30%)	5.7	(15%)	17.8
N_2 PROPELLANT		0.7		0
TOTAL		24.8 kg		136.7 kg
TOTAL (BOTH VEHICLES)				161.5 kg

DRILLING SAMPLER



LANDER SUBSYSTEMS	MASS
SCIENCE	0
COMMAND/DATA HANDLING	1.5
TELECOMMUNICATION	1.2
AACS	1.6
REACTION CONTROL SYSTEM	2.4
POWER/PYRO	3.8
STRUCTURE	13.0
THERMAL CONTROL	2.5
CABLING	0.5
DEVICES	5.8
SUBTOTAL	32.3
N_2 PROPELLANT	0.9
CONTINGENCY (30%)	9.7
TOTAL	42.9 kg

DRILLING SAMPLER/LANDER



LANDER SUBSYSTEMS	MASS
SCIENCE	14.0
COMMAND/DATA HANDLING	16.0
TELECOMMUNICATION	11.2
AACS	0
REACTION CONTROL SYSTEM	0
POWER/PYRO	30.0
STRUCTURE	42.5
THERMAL CONTROL	9.6
CABLING	5.0
DEVICES	10.5
SUBTOTAL	138.8
CONTINGENCY (15%)	20.8
DRILL/RETURN VEHICLE	29.1
TOTAL	188.7

Catching a Comet: Rendezvous and Docking Techniques

Collecting a sample from a comet presents special challenges: finding the comet, landing on it, acquiring the sample, getting away again, and maintaining the sample in pristine condition during the long journey back to Earth. Two of the biggest challenges have not yet been met by robot spacecraft: finding a tiny object, and landing on–or docking with–an object whose gravity field is virtually nonexistent.

For the *Comet Nucleus Sample Return* mission, the initial rendezvous must take place near aphelion, when the comet is far from the Sun. There will be no bright coma or tail to detect. The spacecraft instruments will have to find what is almost the proverbial "black cat in the coal cellar at midnight"–a tiny object, one or two kilometers across, of unknown albedo, in the relatively weak sunlight that is present at about 750 million kilometers from the Sun.

An orderly rendezvous strategy is required: the spacecraft will enter the volume of space that (supposedly) contains the comet from the sunward side, to get the best reflections off its target. Cameras and other detectors will then perform a search pattern. Detection should not be too difficult, because the comet, dim as it is, will probably be the brightest object in the sky. Once the comet has been detected, standard trajectory maneuvers, carried out cautiously but not too slowly, can be used to place the spacecraft in rendezvous with the comet.

Because the gravity of a two-kilometer object is almost zero (the microgravity must, however, be accounted for), the "landing" will be more like docking with another spacecraft. A simple free-fall lander could be used. Such a device would simply drop to the comet's surface and absorb the small impact with crushable material on its footpads. However, the desire to control the landing carefully (and to avoid contamination of the sampling site) will probably call for a more sophisticated lander, with thrusters and radar or laser sensors, for a more delicate touchdown.

Sampling is also a problem. Any force used to obtain the sample puts an equal reaction on the sampler. (This is the essence of Newton's Third Law.) Because the comet's gravity is so low, the mass of the vehicle provides no stability; a hard shove during the sampling operations could turn the lander over or lift it right off the surface. Keeping the vehicle fixed on the surface by continuous use of rocket thrusters would probably use up too much fuel. For this reason, the lander must be firmly anchored to the comet during the sampling operations.

This raises a further question: How do you anchor yourself to something when you don't know what that something is? To design both the anchors and the sample coring tool, we need to understand the nature of cometary material. Current models of comets are not much help; in them, the nucleus material ranges from the equivalent of soft snow to hard glacier ice. Various anchoring concepts, ranging from harpoons to drills, have been suggested, but more data are clearly needed. The scientists and engineers concerned with sampling a comet will be looking with special interest at current and future spacecraft missions–the *Giotto* flyby of Halley's Comet and, particularly, the *CRAF* mission, that will probe the nucleus of a comet more closely.

prevent thermal, chemical, or radiation-induced changes in the sample during the return trip to Earth. Currently available insulation and passive cooling techniques are adequate to maintain the sample at its acquisition temperature during the trip. At Earth approach, solid-fuel retro motors will be fired to inject the capsule into a circular orbit that can be reached by the *Space Shuttle*. **The sample must be recovered rapidly from this orbit in order to minimize thermal alteration in the near-Earth environment.**

Mission Operations

Rendezvous and Sampling Operations

The *Comet Nucleus Sample Return* mission can be divided into five major phases:

1) global characterization of the nucleus;
2) regional site mapping of the nucleus;
3) sampling site selection;
4) sample collection and site characterization;
5) long-term studies from the landed station after sample collection.

After rendezvous with the comet, the global characterization phase of the mission is expected to take six days. During this time, the spacecraft will be stationed approximately 200 kilometers distant from the nucleus, and its imaging system can obtain full-nucleus images at a spatial resolution of about two meters/pixel. Such full-nucleus images will be obtained for a number of different phase angles, sub-spacecraft longitudes, and various spectral wavelengths. These images will provide the necessary information to identify several regions on the surface as candidate sampling sites and, after two more days, to select the actual two target areas.

After global characterization, one day will be needed to transfer the spacecraft to a 50-kilometer altitude at a selected phase angle. From this distance, a global stereographic, multicolor mosaic with a spatial resolution of 50 centimeters/pixel will be acquired. (This period represents the most critical time for protection of optical surfaces from the dust hazard.) The spacecraft will then be transferred to a safer 100-kilometer distance to await the site selection decision.

Based on our earlier experience in selecting *Viking* landing sites on Mars, it is expected that a total of five days will suffice to confirm selection of the first sampling site. The spacecraft will then be committed to that site and will begin to move inward to a distance of ten kilometers from the surface of the comet nucleus. After reaching that distance, the spacecraft will keep station with the comet, while the nucleus rotates beneath it, until the rotation of the nucleus brings the sample site into the proper position with respect to the spacecraft. (This waiting time will be up to one fourth the rotation period of the nucleus.)

Jets of vapor escape the interior of a comet nucleus. Ice pinnacles have been left where the surface was protected from sunlight by clumps of soil.

At that moment, the spacecraft will fire its thrusters continuously to establish a "forced-synchronous" orbit that will keep it in a fixed position over the sampling site, in order to maintain communications with the sampling devices (hereafter called the "samplers"). The first sampler will then be deployed from the spacecraft. The sampler's own attitude control system will maintain the orientation and direction needed to reach the sample site and to execute the landing.

As soon as possible after the sampler lands, the spacecraft will take pictures of the landed sampler and the surrounding terrain, obtaining ground resolutions of ten centimeters/pixel (20 centimeters/line pair) at phase angles of from 0 degrees to 90 degrees. At the end of one complete revolution of the nucleus, when the sampling has been completed, a launch signal will be sent from the spacecraft to the sampler to start its vertical ascent and to rendezvous with the parent spacecraft. The launch must take place when the spacecraft is directly above the sampler in order to ensure rendezvous.

Recovery of the sampler by the spacecraft bus will be carried out using automated rendezvous and docking procedures. Once the spacecraft and sampler are docked, the sample will be transferred to a protective canister within the sample return capsule, a part of the spacecraft bus, after which the auxiliary sampler electronics and structure will be jettisoned. The entire sample collection and site

characterization phase will require approximately 1.5 nucleus rotations at a minimum. The time spent in the sampling phase will be kept to a minimum in order to reduce the dust hazard to the spacecraft.

After the first sample is collected, the spacecraft will return to an altitude of 100 kilometers and await a decision on the second sampling site. Three days are allowed for that decision. Then the sample collection and site characterization operations will be repeated.

The "forced-synchronous" orbit referred to above is required because the comet's low gravity places the natural synchronous orbit at too low an altitude (less than one kilometer above the surface). Higher altitude synchronous orbits are attained by thrusting downward to create artificially the equivalent of a higher gravitational attraction. The thrust needed to generate the "forced-synchronous" orbit will be greater than that available from the low-thrust propulsion system that has been used since launch to establish the proper trajectory and to rendezvous with the comet. **To provide the additional thrust needed to maintain the "forced-synchronous" orbit, it will almost certainly be necessary to provide an auxiliary chemical propulsion system on the spacecraft.**

Environmental Hazards

The chief hazards to the spacecraft during its near-encounter operations are the dust and gas emitted by the active comet nucleus and the thermal background inside the comet's coma. Of these hazards, the dust presents the most serious problem for this mission. The constraints imposed by the dust hazard on the beginning and end of the close cometary encounter affect numerous mission design requirements. The required encounter duration determines the arrival and departure times at the comet, and these in turn influence the interplanetary transfer mode, which in turn affects the performance requirements for this mission and thus drives the mission cost.

Surface Lander and Long-Term Station

The nature of the *Comet Nucleus Sample Return* mission makes possible a unique opportunity to emplace a long-term monitoring station on the surface of the nucleus and thus to make detailed observations of the dynamical behavior of the comet in a manner analogous to the *Viking Landers* on the surface of Mars. The instruments on such a surface station can transmit a wide range of physical, chemical, and dynamical information about the comet itself, and these data will also provide an important context for the effective interpretation of the sample results. The station can characterize *in situ* the bulk physical and chemical properties of the nucleus material near the point where one of the samples was collected. It can also monitor the dynamic activity of the comet for at least several months as the comet moves past the Sun and out into space again.

Detailed measurements from such a surface station can include the chemical, thermal, and mechanical properties of the nucleus material, surface and subsurface temperatures in the nucleus as a function of solar radiation, rates of gas production from the nucleus, and the composition of emitted gas and ice particles. Such data would help link the sample results to the general causes of cometary activity, and the *in situ* information would be especially valuable in case of loss or degradation of the samples themselves during return to Earth.

It would be very desirable for the station to have some limited surface imaging capability. It is likely that only very limited data transmission rates can be supported; the imaging system could therefore be designed to transmit information only if the scene changed. (Most likely, a camera could only be used while the spacecraft was in the vicinity of the comet.)

The station should be designed to operate through one cometary activity cycle, or at least until the comet has moved far enough from the Sun for its activity to cease (roughly, out to the asteroid belt). To make this long operation possible, a 150-watt Radioisotope Thermoelectric Generator (RTG) would be included to provide power to the station. The RTG would be placed on a mast 1.5 to 2.0 meters above the surface so that the radiated waste heat will not exceed the heat received by the comet from the Sun at aphelion. To further reduce potential thermal contamination of the comet, the base of the lander will be sealed and protected by multilayer insulation.

The communications link from this surface station is a challenging problem. Normally, the system would use X-band (or higher) frequencies and a high gain antenna with hemispherical pointing capability to communicate with either the parent spacecraft or directly with Earth. Continuing improvements in the capabilities of the worldwide Deep Space Network (DSN) systems are expected to contribute substantially to this part of the mission.

Summary

The SSEC considers that the return of a sample from the nucleus of a comet is one of the highest priorities for an Augmentation Mission, and such a mission should be undertaken as soon as possible. This achievement would raise the study of comets to a new level and would provide unique and otherwise unobtainable insights into the earliest history of the solar system, the significance of nearby pre-solar events, and the origin of life.

Like the other candidate Augmentation Missions, a *Comet Nucleus Sample Return* provides major technological challenges. In fact, the mission cannot be undertaken without significant technical developments in several fields. Some of the challenges include:

1. Development of a new low-thrust propulsion system required to enable launch from Earth orbit, interception of the comet, and insertion into a rendezvous trajectory.

2. Design of an automated sampling device, able to land and anchor to small objects with negligible gravity, and then able to drill into the nucleus material and recover the core sample.

3. Automated rendezvous and docking techniques to enable the sampler to return from the surface of the nucleus to the parent spacecraft.

4. Automated sample transfer techniques, usable in zero gravity and adequate to transfer a one-meter-long core from the sampler to the sample return module on the parent spacecraft.

5. Thermal and radiation protection techniques for the sample return module for the Earth return leg of the mission.

6. Aerobraking techniques, as a possible alternative to chemical or low-thrust propulsion, for inserting the returned sample module into a *Space Shuttle*-compatible low-Earth orbit from which the necessary rapid sample recovery can be made.

Many of these technologies (e.g., aerobraking and automated rendezvous and docking) are not specific to the *Comet Nucleus Sample Return* mission, and developments in these fields, undertaken for other purposes, will benefit the mission. Similarly, to the extent that these technologies are developed for the *Comet Nucleus Sample Return* mission, there is a real potential for "spinoff" benefits to many other kinds of future space activities.

The development of low-thrust propulsion is especially critical; without such capabilities, the mission cannot be done with a single *Shuttle/Centaur* launch. Solar-electric propulsion is regarded as a minimum enabling technology for the mission, because it will permit access to at least a small group of comets for sampling purposes. The development of nuclear-electric propulsion would result in a much larger set of available target comets. (Some technical alternatives, not considered in this study, might be substituted for low-thrust propulsion. These include: (1) the use of multiple *Space Shuttle* launches with on-orbit assembly of two or more *Centaur* launch stages; (2) use of aerocapture, rather than retropropulsion, for entry into Earth orbit on return.)

Costs for the mission have not been calculated in detail. Approximate estimates lie in the range of $450 to $750 million (FY 1984 dollars), or $675 to $1,000 million with the transportation costs included. The large range in estimated costs reflects a range of possible mission design choices regarding the target comet, the flight mode, the nature of the samplers, and the option to include a long-lived surface station on the comet's nucleus.

The *Comet Nucleus Sample Return* mission has been studied in much less detail than the *Mars Sample Return*. **This lack should be remedied, and the required studies on exact mission requirements, exploration and sampling scenarios, necessary technical developments, and costs should be started**. Because of the significant technical demands of the mission (especially in such areas as low-thrust propulsion), the necessary studies should be undertaken at once.

CONCLUSIONS

1. The SSEC strongly concurs with the recommendation of the National Academy's Committee on Planetary and Lunar Exploration (COMPLEX) that the highest priority in cometary studies is to determine the composition and physical state of the cometary nucleus. (This conclusion also underlies the recommendation for an early comet rendezvous mission in the Core Program.)

2. No mission short of a *Comet Nucleus Sample Return* can provide the range and detail of analyses needed to definitively characterize the composition and structure of the comet nucleus material.

3. It is now technologically within our reach, in terms of current and foreseeable technological developments, to collect pristine samples directly from active comets and to return them to Earth for intensive laboratory study.

4. A precursor comet rendezvous mission is needed to determine at close range the nature and characteristics of a comet nucleus. The comet selected for sample return should have properties similar to those of the comet visited in the rendezvous mission.

5. Characterization and selection of the sampling site on the nucleus can be done by close-range remote sensing. Sampling can be accomplished in a short period of time by a recoverable nucleus sampler.

6. A deep core sample (one-meter length) is essential to obtain primordial cometary material that has not been altered by surficial processes–solar heating, outgassing, particle impacts, and radiation damage.

7. Low-temperature preservation (less than 120° K) of the sample from the time of collection is essential in order to preserve the original organic and volatile components, the original structure of icy materials, and the original associations between volatile and solid materials. The samples can be maintained at these temperatures by a combination of insulation and passive cooling techniques.

8. In order to minimize degradation of the samples in the vicinity of Earth, the returning spacecraft should be placed in an Earth orbit from which it can be reached by the *Space Shuttle*, and the samples should be quickly retrieved from orbit.

9. The *Comet Nucleus Sample Return* mission requires more propulsive capability out of Earth orbit than can be provided by any single launch stage, including the *Centaur*. To make the mission compatible with a single *Centaur* launch, development of some type of low-thrust propulsion system (either solar-electric or nuclear-electric) is essential.

10. Auxiliary propulsion capabilities (such as solid-fuel rocket motors) are required for essential high-thrust mission operations: (a) maintaining a "forced-synchronous" orbit around the comet nucleus during the sample collection operations; (b) inserting the returning spacecraft into a *Space Shuttle*-compatible Earth orbit from which the sample can be rapidly recovered. Aerocapture may provide an alternate method for Earth-orbit insertion.

11. The *Comet Nucleus Sample Return* mission cannot be undertaken without additional technical developments in several other fields, including: automated rendezvous and docking, aerocapture, automated sampling and sample transfer techniques, and thermal and radiation protection systems.

12. The mission offers the highly desirable opportunity to emplace a long-lived instrumented surface station on the comet's nucleus during the sample collection operations. The addition of such a station has little effect on launch margins or other mission requirements. The station can supplement the information obtained from the returned samples by providing long-term data about the composition, structure, and dynamical behavior of the comet. It is very desirable that the station have some limited imaging capability.

13. Approximate estimates of mission costs are in the range of \$450 to \$750 million (FY 1984 dollars), and \$650 to \$1,000 million if transportation costs are included. The large cost range reflects a range of mission design choices regarding the target comet, the flight mode, the type of samples, and the option to include a long-lived surface station.

RECOMMENDATIONS

1. The SSEC considers that the return of a sample from the nucleus of a comet is one of the highest priorities for an Augmentation Mission. The SSEC therefore recommends that this mission should be undertaken as soon as possible.

2. The present lack of detailed studies about a *Comet Nucleus Sample Return* mission (i.e., in comparison with a *Mars Sample Return* mission) should be remedied immediately by undertaking the studies necessary to define in detail the scientific rationale, mission requirements, spacecraft systems, and costs for the mission.

3. Detailed study and development of specific technologies required for the mission should also be undertaken as soon as possible, especially in such areas as low-thrust propulsion, automated rendezvous and docking, aerocapture, automated sampling and sample transfer techniques, and thermal and radiation protection. Special attention should be given to the development of a low-thrust propulsion system, because such a capability is essential to make the mission compatible with a single *Shuttle/Centaur* launch.

Icebergs floating on a nitrogen sea are features of a recent hypothesis for the composition of Neptune's giant moon, Triton.

5. The Realm of the Giants

MISSIONS TO THE OUTER PLANETS

New Worlds, New Questions

The brief encounters of the *Voyager* spacecraft with the Jupiter and Saturn systems dramatically demonstrated that the outer solar system contains a dazzling array of potential targets for future planetary exploration. Beyond the asteroid belt lie four giant ringed planets (Jupiter, Saturn, Uranus, and Neptune), more than 50 moons (two of which–Titan and Ganymede–are larger than the planet Mercury), at least two planetary magnetospheres larger than the Sun itself, and the curiously small world Pluto. The center of gravity of our planetary system is here; these worlds (chiefly Jupiter and Saturn) account for more than 99 percent of the mass of the solar system, excluding the Sun.

Exploration of the outer planets, especially Jupiter, can provide unique insights into the formation of the solar system and the universe itself. Because of their large masses, powerful gravitational fields, and low temperatures, these giant planets have retained the hydrogen and helium that they collected from the primordial solar nebula. The abundance and isotopic composition of these elements in the atmosphere of Jupiter, for example, can provide fundamental clues to the formation of the solar system 4½ billion years ago. Such measurements could, in fact, carry us even further back in time; Jupiter's atmosphere might even "remember" the formation of cosmic hydrogen and helium in the original Big Bang and the changes in these elements within the Galaxy long before the solar system formed.

In addition to their primordial bulk chemistry, these giant planets will certainly provide other clues to help us unravel the history of the solar system. Chemical reactions, including the formation of organic molecules, are now taking place in the atmospheres of the giant planets and of Saturn's moon Titan. These reactions, which are probably responsible for the color bands of Jupiter and the murky haze that shrouds Titan, may resemble some of the pre-biotic chemistry of primitive Earth and may therefore help us to study some of the pathways to our own beginnings.

Furthermore, studies of the movement of ring particles and their perturbation by larger planetary moons provide analogues for studying the dynamical processes that occurred in the primordial solar nebula. The various planetary ring systems in the outer solar system can therefore fill in large gaps in our understanding of the protoplanetary stage of solar system formation.

Because of the vast magnetospheres that surround them, the outer planets (especially Jupiter and Saturn) have an importance that extends far beyond the normal boundaries of planetary science. The brief penetrations of Jupiter's and Saturn's magnetospheres by the *Pioneer 10* and *11* and *Voyager 1* and *2* spacecraft revealed intense electric and magnetic fields, a diverse population of charged ions, a series of complex mechanisms that accelerate the ions, and a variety of interactions between the plasmas, their gas-rich planets, and the solid moons. In the current era, these magnetospheres have become natural laboratories for testing theories about astrophysical plasmas and their interactions with magnetic fields and solar particles, and in them we can make observations on a scale not possible in a terrestrial laboratory or even in the space environment of Earth itself.

Greatly augmenting the scientific richness of the outer planets themselves are the diverse moons which orbit the planets and which range in character from fire to ice. Each of these tiny worlds is unique, and together they span the complete range of planetary processes and time scales. The battered surface of Callisto preserves a record of the original impact cratering that accompanied the formation of the solar system, while the active volcanic landscape of Io was changing even as the *Voyager* spacecraft photographed it. Other moons have their own mysteries–the strangely mobile, icy crusts of Ganymede and Europa, the still-mysterious light-dark surface of Iapetus, the unknown surface of Titan, which is totally concealed by that moon's thick and murky atmosphere–and all of these moons are sites for scientific explorations no less important or exciting than the giant planets themselves.

Exploration of the Outer Planets

The giant worlds of the outer solar system differ greatly from the smaller terrestrial planets, and it is not surprising that different strategies have been developed to explore them. The long-term exploration goal for terrestrial planets and small bodies is the return

The Outer Solar System: An Array of New Worlds

Displayed below are the basic statistics for the strange worlds of the outer solar system. (The data for Uranus include the results of the *Voyager 2* encounter in January, 1986.)

The four giant planets (Jupiter, Saturn, Uranus, and Neptune) have a strong family resemblance. They are all many times as large as Earth, they have low densities, they are composed chiefly of low-temperature materials (gases and ices), and they are accompanied by rings and by large numbers of moons. Even within this family, however, there are differences. Jupiter and Saturn are much larger than the "twins" Uranus and Neptune, and they apparently contain more hydrogen in proportion to other compounds like ammonia and methane

Pluto, the outermost planet, is an anomaly. It would be much more at home as an icy satellite of one of the giant planets. Pluto is tiny (smaller even than our Moon) and probably icy (its density is close to that of water ice). Theories on the formation of Pluto, ranging from an escaped moon of Neptune to a large planetesimal that avoided being accreted by one of the giant planets, must now take into account the recent discovery of Pluto's moon, Charon.

	EARTH	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Diameter (kilometers)						
Equatorial	12,756	142,800	120,000	52,000	48,400	3,000
Polar	12,714	134,200	108,000	49,000	47,400	3,000
Inclination of Equator to Orbit (degrees)	23.44	3.12	26.73	97.86	29.56	90
Mass (kilograms)	5.9742×10^{24}	1.899×10^{27}	5.684×10^{26}	8.6978×10^{25}	1.028×10^{26}	6.6×10^{23}
Density (H_2O = 1)	5.52	1.32	0.70	1.25	1.77	1.5
Escape Velocity (kilometers/second)	11.18	59.6	35.6	21.1	24.6	7.7
Volume (Earth = 1)	1	1323	752	64	54	0.01
Surface Gravity (Earth = 1)	1	2.69	1.19	0.93	1.22	0.20
Period of Revolution Around Sun (years)	1	11.9	29.5	84.0	164.8	247.7
Mean Distance From Sun (astronomical units)	1	5.2	9.5	19.2	30.1	39.4
Number of Moons	1	16	23	15	3 (?)	1
Rings?	NO	YES	YES	YES	(?)	NO
Period of Rotation	$23^h 56^m$	$9^h 55^m 40^s$	$10^h 39^m$	$17^h 18^m$	$15^h 40^m$	153^h
Gases in Atmosphere	N_2, O_2, Others	H_2, He, NH_3, CH_4, Others	H_2, He, CH_4, NH_3, Others	CH_4, H_2, He	CH_4, H_2, He	CH_4 (thin)
Internal Structure (estimated)	Fe-Ni Core, Silicate Mantle, Rigid Rocky Outer Crust, Surface Ocean (Liquid H_2O), Atmosphere (mostly N_2, O_2)	Ice-Silicate Core, Liquid Metallic H_2 Mantle, Liquid Molecular H_2 Envelope, Atmosphere	Ice-Silicate Core, Liquid Metallic H_2 Mantle, Liquid Molecular H_2 Envelope, Atmosphere	Rocky Core, Mantle of ion-enriched liquid H_2O, Thick H_2, He Atmosphere	Rocky Core, NH_3, CH_4, H_2O Ice Mantle, Thick "crust" of compressed H_2 and He grading into the atmosphere	?

of samples to terrestrial laboratories, but the basic technique for studying the gas-giant planets is the *in situ* analysis of their atmospheres by means of atmospheric probes.

Such atmospheric measurements, which will be undertaken for the first time by the *Galileo* probe at Jupiter, provide the only complete compositional information that can be obtained from a body whose solid surface (if any) lies inaccessible under tens of thousands of kilometers of dense atmosphere. Atmospheric probe measurements, like measurements on returned samples, will provide critical information about cosmology and planetary evolution and will permit fundamental distinctions to be made between the different outer planets themselves. These *in situ* analyses will also avoid the extreme difficulties involved in collecting a gas sample from a high-gravity planet and transporting it, unaltered, to a terrestrial laboratory–problems additional to those involved in the return of rock or even ice samples from small bodies.

The outer planets present special challenges which affect both the execution of the Core Program Missions and the planning of possible Augmentation Missions. The greatest problem is our relative ignorance about all of the outer planets; a first-order data base will not be complete until after the *Galileo* mission to Jupiter, the *Voyager* encounters of Uranus and Neptune, and the use of the *Hubble Space Telescope* for observations of the outer planets.

Building up our information has been a slow process because of the long travel times for outer planet missions imposed by existing propulsion systems. Currently achievable travel times range from about seven years to Saturn to about 15 years to Uranus, and these long durations make it difficult to execute many missions, even in the Core Program, before 2000, especially for the worlds beyond Saturn.

To undertake missions beyond the scope of the Core Program, we will need to transport heavier spacecraft into the outer solar system and to do it more rapidly. For such Augmentation Missions, there are numerous and diverse technological needs besides improved launch systems–aerocapture and aeromaneuvering, robotics, and the development of electronic and mechanical components that are long-lived and also resistant to heat, cold, and especially radiation.

The outer planets also provide us with a special challenge which mainly affects the planning of Augmentation Missions–one that can be succinctly described as an embarrassment of riches. The outer solar system presents an overwhelming number of potential targets and possible missions with a wide variety of scientific yields. Targets include: the planets, the larger moons (Titan, Triton, and the diverse Galilean satellites), the smaller moons, the rings, and the magnetospheres. Possible missions could include: combined orbiter/probes, hard or soft moon landers, ring rovers, atmospheric buoyant stations, and magnetosphere explorers.

The combination of an incomplete data base and the great number of conceivable missions makes it inappropriate to select *at this time* a single mission, or even a single class of missions, as the highest-priority candidates for Augmentation Missions to the outer planets. This situation differs from the case of the terrestrial planets

and small bodies, for which, with our present state of knowledge, we have been able to identify specific sample return missions as the highest priority for Augmentation Missions.

In this chapter, we provide a scientific rationale for future outer planet Augmentation Missions in order to indicate some especially exciting candidates for further study and to clearly identify some technological requirements for Augmentation Missions of any type. However, selection of specific missions must wait until the data are more complete and some of the possible missions have been studied in more detail.

Exploration Strategy for the Outer Planets

In comparing the status of exploration of the outer planets with the three stages of planetary exploration defined by COMPLEX, the *Reconnaissance* stage, consisting of flyby missions and Earth-based observations, will be essentially complete (except for Pluto) by 1990, with the *Voyager* flybys of Uranus and Neptune. No encounter is planned for Pluto, but study of this planet should be improved by observations using the *Hubble Space Telescope* when it is launched. The recently begun ground-based observations of eclipses between Pluto and its moon Charon have considerable potential for extending our knowledge of these distant worlds, and they serve as an example of what future, more sophisticated Earth-based observations may achieve.

The *Exploration* stage, involving long-term global studies by orbiters and probes, will be reached for Jupiter by the *Galileo* mission and will be provided, to some extent, for the more distant outer planets by subsequent missions in the Core Program. These missions will involve orbiter and probe studies of the Saturn-Titan system (perhaps combined into a single international mission called *Cassini*) and a flyby/probe mission to Uranus. Current plans do not call for a *Neptune Flyby/Probe* mission before 2000.

The Core Program Missions will emphasize studies similar to those carried out for Jupiter: atmospheric composition by *in situ* analyses; atmospheric dynamics (long-term observations); detailed mapping of satellites and magnetospheres; and detailed observation of ring dynamics. Saturn's moon Titan, Neptune's large moon Triton, and the still-unvisited planet Pluto are objects of special interest at this stage.

Intensive Study missions, focused on specific major scientific problems, will have to be based on results from the *Reconnaissance* and *Exploration* stages and especially on data from the *Voyager* and *Galileo* missions. Intensive study missions may include deep atmospheric probes, atmospheric buoyant stations (especially on Titan), hard-landed surface networks, soft landers, and advanced orbiters. All these efforts will be, by definition, Augmentation Missions; they cannot be accommodated within either the funding resources or the launch capabilities available to the Core Program. Any of these Augmentation Missions will generate rich yields of

Anatomy of a Giant: A Slice Through Jupiter

Jupiter, fifth planet from the Sun and ten times the diameter of Earth, is the largest of the four gas-giant planets found in the outer solar system. Unlike the smaller terrestrial planets, which are made up primarily of metal and rocky silicate materials, Jupiter is mostly made of hydrogen and helium, together with small amounts of other elements found in nearly the same proportions as in the Sun. Jupiter is, in fact, a big ball of gas with a dense core, almost starlike but not big enough to have become a star.

The interior of Jupiter, hidden beneath its belts of white and pastel clouds, is a strange place. Its nature is dominated by the properties of hydrogen (its most abundant ingredient), by the tremendous pressures produced by the thick layer of overlying gas, and by high temperatures maintained (at least partly) by the continuing slow contraction of the planet since it was formed.

Most of Jupiter's interior (we think) is liquid hydrogen. There is probably a dense core of rocky material, with about ten to 15 Earth masses at the very center of Jupiter. Deep inside Jupiter, where pressures reach millions of atmospheres, the hydrogen is transformed into a metallic state, in which its electrons are free to conduct the electric currents that produce the planet's huge magnetic field. Above this metallic region is a thick layer of "normal" liquid hydrogen. Above this layer, where pressures are relatively low, the hydrogen becomes a gas, forming an atmosphere thousands of kilometers deep.

The subtly colored cloud layers visible to telescopes and spacecraft are near the top of Jupiter's atmosphere and represent only a tiny fraction of the material that composes the planet. A wide variety of cloud layers are known or suspected to exist. From the top down, they are: a thin hydrocarbon "smog"; ammonia; ammonium hydrosulfide; water ice; and liquid water. The ingredients that produce the colors in the clouds are caused by small amounts of chemicals that have not yet been definitely identified. They may include sulfurous or phosphorous compounds, as well as organic (carbon-containing) polymers.

scientific data, and all of them will require the development of major new technologies.

Even though no one outer planet Augmentation Mission can be singled out at this time, a number of exciting candidates can be identified for further study. These include: (1) deep atmospheric probes (500 atmospheres) to reach the deep levels of the atmospheres of Jupiter and Saturn, or to penetrate beneath the water layers of Uranus and Neptune, and thus obtain a bulk compositional measurement for these planets; (2) combinations of hard landers, penetrators, and soft landers for the various satellites, which could determine surface compositions and emplace a variety of seismic, heat-flow, and other instrumental networks; (3) close-in magnetospheric studies in regions where the radiation is too intense for existing equipment; (4) detailed studies of Titan, carried out by balloons or surface landers; (5) close-up, long-term observations of Saturn's rings, carried out by a so-called "ring rover" spacecraft able to move within the ring system.

The Foundation: Core Program Achievements for the Outer Planets

The SSEC recommended a series of Core Program Missions whose goal is to achieve an *Exploration* level of understanding for the outer planets as far out as Uranus. This recommended program emphasizes the comparative study of the atmospheres of the outer planets and of Saturn's moon Titan by means of a series of

A probe penetrates the deep cloud layers of Neptune's atmosphere.

atmospheric entry probes that are basically similar to the *Galileo* probe. These probes would be delivered by a new, efficient *Voyager/Galileo* class spacecraft called *Mariner Mark II*. As the *Voyager* experience has already shown, such a spacecraft can conduct extremely powerful remote sensing observations as well as making *in situ* magnetospheric measurements.

Specific Core Program Missions recommended by the SSEC are:

- *Titan Flyby/Probe*
- *Saturn Orbiter*
- *Saturn Probe*
- *Uranus Flyby/Probe*

A *Neptune Flyby/Probe* and a *Pluto Flyby* mission must clearly be added as soon as possible to provide consistency and continuity with the Core Program, even though it is recognized that they will probably not be launched before 2000. (It was *only* this time constraint that kept these missions from being included as high-priority items in the recommended Core Program.)

Saturn is a special case in the Core Program. Although the original Core Program was constructed with separate *Saturn Orbiter*, *Saturn Probe*, and *Titan Probe* missions, it is, in fact, possible to conduct a combined orbiter/probe mission (similar to the *Galileo* orbiter/probe mission to Jupiter), using a *Mariner Mark II* spacecraft, without exceeding the capability of the *Shuttle/Centaur* launch vehicle. (This possibility does not exist for the more distant outer planets.)

Such an orbiter/probe mission to Saturn should be carried out if at all possible, because it would greatly accelerate the Core Program by combining two separate missions into a single effort. In addition to direct atmospheric analyses of Saturn or Titan, the combined mission would provide multiple close satellite encounters, extended observations of Saturn's rings from many different points of view, and a detailed, long-term study of the saturnian magnetosphere.

The possibilities for such a combined orbiter/probe mission lead naturally to the potential for international cooperation in carrying out the undertaking. Joint NASA-ESA discussions and studies are now going on to examine the combination of the two Core Program Missions into a single cooperative *Saturn Orbiter/Titan Probe* mission (called *Cassini*). The other missions of the Core Program also provide numerous potential opportunities for international cooperation. These possibilities are being, and should continue to be, studied in more detail as the Core Program progresses and evolves.

Combined with results from the *Voyager* and *Galileo* missions, the first four outer planet Core Program Missions (to Saturn, Titan, and Uranus) will make a historic contribution to planetary science and will provide a solid data base for planning Augmentation Missions. Accomplishments of the Core Program will include:

- Long-term measurement of the atmospheric dynamics of Jupiter and Saturn;

- Direct atmospheric analyses of Jupiter, Saturn, Titan, and Uranus;
- Radar mapping of the surface of Titan, which is now the largest unknown planetary surface in the solar system, equal to the combined areas of Asia, Africa, and Europe;
- Detailed, high-resolution multispectral mapping of the Galilean and Saturnian satellites;
- Long-term three-dimensional observations of the magnetospheres of Jupiter and Saturn;
- Long-term studies of the dynamics of Saturn's rings.

Despite the achievements of the Core Program, significant gaps will still remain in our knowledge of the outer planets by the year 2000. There will be no orbiter missions beyond Saturn, no post-*Voyager* missions to Neptune, and no missions at all to Pluto. These outer worlds will still be at the *Reconnaissance* (or, in the case of Pluto, the pre-*Reconnaissance*) level of exploration by the year 2000.

This situation reflects the fact that the recommended Core Program assumed a funding level of $325 million/year (FY 1984 dollars) between now and the end of the century. With these restraints, missions to Neptune and Pluto will require that the outer planet portion of the Core Program be continued into the first decade of the next century. It is to be hoped that, by that time, new propulsion technologies will be available that can significantly reduce the travel times needed for such missions. Such improved capabilities, combined with the development of aerocapture techniques, would make possible orbiter or orbiter/probe missions to Uranus and Neptune–the obvious next steps in the post-*Voyager* exploration of these two planets. Such missions would represent essential augmentations to the Core Program that would bring our understanding of Uranus, Neptune, and Pluto to the level now achieved for the inner planets.

Beyond the Core Program: Augmentation Missions

The most essential requirement for the detailed evaluation and selection of Augmentation Missions to the outer solar system is the information to be returned from the outer solar system by current and future missions (*Voyager, Galileo,* and perhaps *Cassini*). These results will make it possible to characterize many of the potential targets (especially Jupiter, Saturn, Titan, and the Galilean satellites) at a level at which major scientific questions can be defined and the spacecraft and instruments for Augmentation Missions can be designed. **The Core Program should therefore be carried out as expeditiously as possible in order to provide this data base at the earliest possible opportunity.**

However, the consideration of Augmentation Missions should not be postponed until these data are available. Even before the data return in the late 1980s and early 1990s, it will be possible to examine in some detail candidate Augmentation Missions that can

be devised on the basis of results of the Core Program. It is immediately clear, for instance, that major technological developments are needed in several areas before any missions beyond the Core Program will even be possible, and much of this technological development should be undertaken in the near future. Such studies should be begun at once in order to identify in detail the scientific and technical requirements for such missions.

New propulsion technologies are probably the greatest single technological development needed to make Augmentation Missions possible. The inadequacy of the *Shuttle/Centaur* combination to launch them is common to all the candidates. Accordingly, major advancements in launch capability and, most likely, in aerocapture/aeromaneuver capabilities as well, are essential if the exploration of the outer solar system is to proceed beyond the *Galileo* level or to examine in any detail the worlds beyond Saturn. These technologies are in fact generic requirements for nearly all Augmentation Missions; they are specifically required for the *Mars Sample Return* and *Comet Nucleus Sample Return* missions described elsewhere in this report.

The necessary propulsion capabilities can be achieved in several different ways or perhaps by a combination of techniques: use of the Space Station for staging; development of solar-electric or nuclear-electric propulsion; and the use of aerocapture/aeromaneuvering capabilities developed for the *Mars Sample Return* mission. **The SSEC recommends, therefore, that Augmentation Missions to the outer solar system be studied further in sufficient detail to understand the required launch and braking requirements and that these requirements be taken into account when implementing the technological developments needed for the sample return Augmentation Missions.**

Other technological developments are required. A brief consideration is sufficient to identify several, and more detailed studies should be carried out as soon as possible. Needed technologies for the Augmentation Missions to the outer planets, in addition to propulsion and aerocapture techniques, include:

- New communications techniques suitable for deep atmospheric probe missions;
- Radiation-hardened components and instruments that can operate for long periods of time in the hostile environment of the magnetosphere of Jupiter;
- Robotic developments that will make possible long-lived autonomous spacecraft, landers, and rover systems;
- Atmospheric balloon technology applicable to balloon probes of the atmospheres of Titan, Jupiter, and other worlds;
- Low-temperature technology for instruments needed to operate on Titan or in the colder environments of the worlds beyond Saturn;
- High-temperature technology for other instruments. Despite the general coldness of the outer solar system, such instruments are needed to study Io and the deep atmospheres of the planets.

Voyager 2 at Uranus: Close Encounter with a Blue Planet

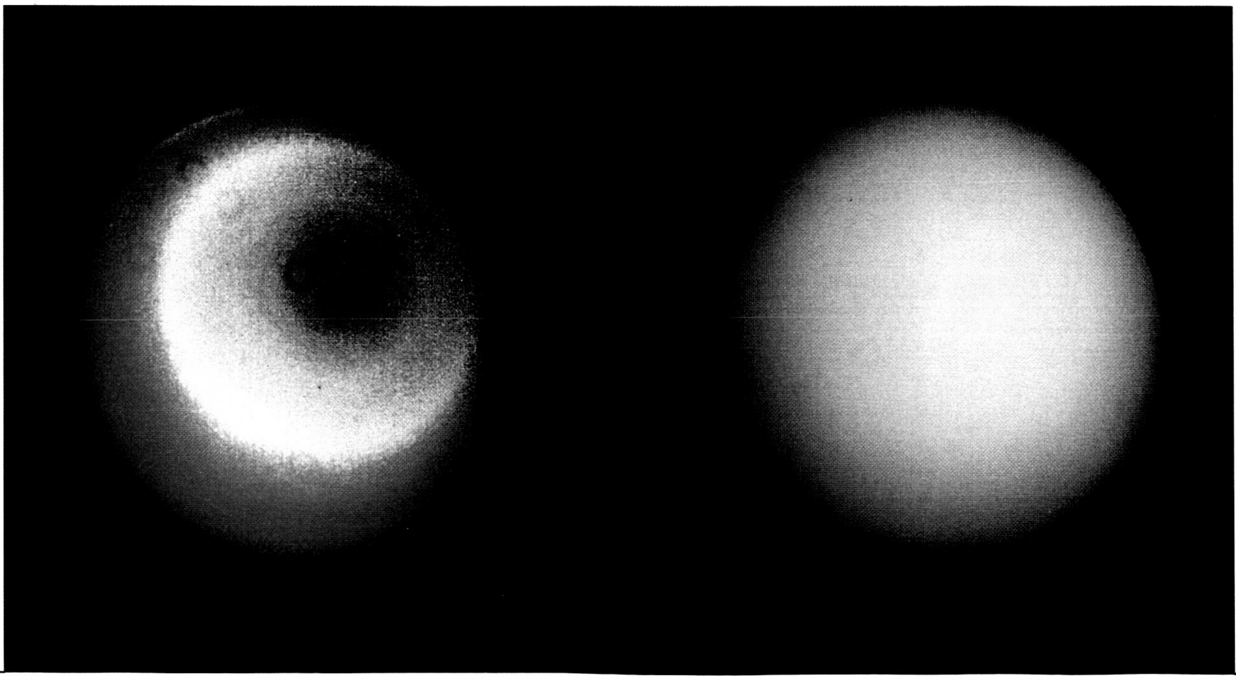
"When the Voyager 2 mission scientists gathered at the Jet Propulsion Laboratory in Pasadena, California, for the spacecraft's late-January encounter with Uranus, they were presented in quick succession with one rakishly tilted magnetic field, one perversely circulating atmosphere, an ever-increasing number of charcoal-black rings, and five inexplicably dingy moons–three of which seemed highly improbable when examined up close, and two of which seemed flatly impossible."

–M. Mitchell Waldrop, *Science,* 28 February, 1986

The marvelous strangeness and unpredictability of the outer solar system were again displayed in *Voyager 2*'s third planetary encounter, this time with the distant and almost-unknown planet Uranus. Uranus and its "twin" Neptune represent a new type of planet that has never been studied up close before. They are gas giants like Jupiter and Saturn, but they are smaller (only about four times the diameter of Earth), and they have more shallow hydrogen-helium atmospheres than do their larger relatives. Uranus has its own peculiarities; its axis of rotation lies almost exactly in the plane of the ecliptic (rather than at a high angle to it, as is the case with the other planets), and during the *Voyager* encounter, the planet's south pole was aimed almost directly at the Sun. Furthermore, it has no internal heat source, no satellite larger than Earth's Moon, and no satellites moving in highly inclined or highly elliptical orbits.

Seen on approach by *Voyager,* Uranus was a bland planet. Its blue-green atmosphere, the red subtracted by methane, showed almost no structure at all, in contrast to the turbulent colors of Jupiter and the sober but distinct stripes of Saturn. Careful examination, and a great deal of image enhancement, finally revealed some subtle banding, together with a few clouds, in the atmosphere. Even though the planet's southern hemisphere was being heated by the Sun, the banding was arranged in zones along latitude lines (like the bands on Jupiter and Saturn). Therefore, such zonal banding is controlled by the planet's rotation and not by heating of one part of its atmosphere.

The southern hemisphere of Uranus as seen through the* Voyager *cameras, shown in false color (left) and as the human eye would perceive it (right).



Despite the apparent blandness of the atmosphere, there is considerable activity going on: by tracking the motions of the clouds, *Voyager* scientists found wind speeds of about 100 meters/second (about 225 miles per hour). Contrary to firm theoretical predictions that the winds of Uranus would blow in a direction opposite to the planet's rotation, the actual winds were blowing stubbornly and definitely in the same direction. Furthermore, the dark pole (hidden from the Sun for 21 years) was at the same temperature as the sunlit pole. The reasons for these characteristics are not yet understood.

Determining the rotation rate of a featureless planet is not straightforward, but scientists were helped by another peculiarity of Uranus. Like Jupiter and Saturn, Uranus also turned out to have a magnetic field, but its orientation was totally unexpected. Instead of being aligned within ten to 15 degrees of the planet's axis of rotation, as is the case elsewhere in the solar system, Uranus' magnetic axis is inclined at about 55 degrees to its rotation axis. As the planet rotates, this misalignment produces twists in the magnetic field, and measuring these distortions provided an accurate estimate of the planet's rotation rate–17 hours, 18 minutes.

During its fast six-hour passage through the Uranus system, *Voyager* obtained distant views of four large moons (from the outside in, Oberon, Titania, Umbriel, and Ariel) and close-ups of the smaller innermost moon, Miranda. By rights, the four large outer moons should have formed a similar-looking family. They are all similar in size (1,200 to 1,600 kilometers in diameter), probably all made primarily of ice, and with such low surface temperatures (only 80 degrees above absolute zero) that geologic activity would seem impossible.

However, instead of four identical "cratered iceballs," *Voyager* discovered four very different individual worlds. To begin with, despite their icy nature, they were all dull and dark, reflecting only about 20 percent of the light that falls on them. Searching for an explanation, scientists suggest that methane or carbon monoxide ice in the surface materials could be responsible. As these ices are bombarded by high-energy charged particles from Uranus' radiation belt, they would decompose and form dark carbonaceous organic compounds that could explain the observed darkening. Alternatively, some of this dark material may have been available from the origin of the solar system. Studies of comet nuclei suggest this, but much more work on this problem is needed.

A further problem is that most of the inner moons seem to have been more geologically active than the outer ones. Oberon, the outermost moon, is heavily cratered but shows no signs of internal activity. Titania, the next inward, displays both craters and a complex system of trenches, valleys, and scarps produced by subsidence and indicating internal geologic activity. Ariel is even more crisscrossed with valleys and scarps, and some of the valleys seem to be filled with some kind of icy "lava" erupted from within the moon. However, Umbriel is a puzzle. It orbits Uranus between two apparently active moons, Titania and Ariel, but it looks old, heavily cratered, totally inert, and yet it is remarkably dark.

Voyager obtained its best pictures of the innermost moon Miranda, an object now regarded as perhaps the most baffling satellite in the solar system. The moon, only 500 kilometers in diameter, is a literal patchwork of different strange terrains–heavily cratered regions like the highlands of the Moon, grooved landscapes like those seen on Ganymede, and huge trenches with sheer cliffs higher than Mt. Everest. The strangeness and diversity of the Miranda landscape have generated serious speculation that this moon was actually assembled out of ill-assorted chunks of a previous moon that was disrupted in some unknown early catastrophe, perhaps a collision with some object large enough to shatter it. No other idea has even come close to explaining what the *Voyager* cameras saw.

As the serious study of the data continues, *Voyager 2* speeds on to an August, 1989 encounter with Uranus' sister planet, Neptune. Reacting to the unsuspected riches in the Uranus results, no one has yet ventured any serious predictions of what *Voyager* will find there.

Where Do We Go from Here?

Although it is not feasible to recommend a single Augmentation Mission or group of missions as the highest priority for the outer solar system, it is worthwhile to indicate some possible targets, to describe the scientific rationale for studying each one, and to suggest briefly the types of Augmentation Missions that might be appropriate for them. For purposes of discussion, we have included the following possible targets: Jupiter, Io, Saturn's rings, Titan, and Neptune's moon, Triton. (The missions described for Io can be applied with little modification to many other airless satellites.) These examples are not intended to be a complete list or to imply any priority.

We recognize that the existing data base is not adequate for detailed considerations, and we have emphasized, in the discussions which follow, the examination of scientific questions that will not be answered by the Core Program Missions. More detailed studies of possible Augmentation Missions should be undertaken as soon as possible and should be modified and updated as new data are received from current and Core Program Missions: *Voyager, Galileo,* and (possibly) *Cassini.*

JUPITER

Identification of an Augmentation Mission to Jupiter will need to await evaluation of the data returned by the *Galileo* orbiter/probe mission. One possibility, however, would be more comprehensive orbiter/probe missions that would emphasize expanded studies of the planet's atmosphere and magnetosphere.

The atmosphere of Jupiter, which will be directly analyzed for the first time by the *Galileo* probe, will almost certainly provide new and unsuspected questions for further study. Even after *Galileo* it will probably be desirable to carry out more precise long-term measurements of atmospheric composition and dynamics and to probe directly the deeper, hotter levels of the atmosphere that are beyond the reach of the *Galileo* probe.

One mission might involve multiple atmospheric probes capable of deeper penetration. Such a mission would place major demands on the spacecraft. For instance, we do not now have entry systems capable of protecting an atmospheric probe that enters Jupiter's atmosphere at high latitudes; as a result, both the polar regions and the fascinating Great Red Spot lie beyond the reach of direct analysis. Furthermore, we do not yet have a means of communicating with a probe at great atmospheric depths, a situation that will require some special technical solutions. The probes may need to be programmed to record data at great depths and then to rise to more accessible levels to transmit it, or it may be possible to use a wire or fiber-optical connection from the probe to a buoyant station that could relay the data from higher up in the atmosphere. Another desired goal, the long-term survival of atmospheric probes, might be achieved by the use of balloons. Such a technique, recently

demonstrated by the U.S.S.R. *VEGA* missions to Venus, could, with further development, be used on Titan. The maintenance of long-term communications between such a balloon probe and an orbiter would also pose challenging problems.

A separate mission, or one combined with an atmospheric multiprobe, could be a sophisticated orbiter capable of detailed mapping of the planet and its moons or of making wide orbital excursions to study Jupiter's magnetosphere and the Io torus.

IO

As the only volcanically active object (other than Earth) identified in the solar system so far, Io is especially attractive for further scientific study. Most of the techniques used to study Io would be equally appropriate for other satellites in the outer solar system (with the exception that the equipment and instruments used on Io will require much more extensive radiation shielding than will missions to other satellites).

Major unanswered questions for Io involve the moon's heat flow, the thickness of its crust, the degree of internal melting, the nature of the chemical compounds on the surface and in the active "lava lakes," and the nature of the "plumbing" that underlies the active volcanoes.

An initial Augmentation Mission to Io might involve the deployment of a network of hard landers or penetrators to establish a long-lived instrument network across the moon. This network could observe, for long periods of time and on a global basis, such phenomena as chemistry, seismic events, heat flow, and transient gas emissions. A later mission could involve a soft lander or armored rover which could survive the intense radiation field and make detailed geologic measurements along a series of surface traverses.

THE RINGS OF SATURN

The proposed *Cassini* mission, or its equivalent in the Core Program, will provide a new level of knowledge about the rings of Saturn, but there will still be questions to be answered about this magnificent and complicated system when the mission is completed. A truly rigorous study of the rings will almost certainly require a spacecraft which can orbit (under power) directly above the various rings and which also has the capability to change its orbit in order to make a complete and long-term survey of the entire ring system.

Such a "ring rover" could make direct observations of ring particles when it is outside the ring plane. Alternatively, it could be inserted into a ring to serve as a "test particle" itself, with its motion being carefully tracked to determine the various forces acting on it at various positions in the rings.

Nuclear-electric propulsion (NEP) is probably essential to provide the necessary mobility for the "ring rover" over long periods of time. The capability for continuous thrusting available from NEP

A Menagerie of Moons

The moons of the outer solar system provide an incredible variety of mysterious worlds that range–literally–from fire to exotic ices. One moon (Io) is in continuous volcanic eruptions. Another (Callisto) displays an icy crust that has not changed in the last 4.5 billion years. Titan has a murky nitrogen atmosphere, denser than our own, rich in organic materials, that hides its surface from view. Iapetus has two faces, one dark, one bright. The distant moons of Uranus, made chiefly of ice, have revealed to the *Voyager 2* spacecraft a series of wild landscapes, shaped by geologic processes whose nature can only be guessed. Here too we find dark coatings, but different from the dark surface of Iapetus. Even distant, tiny Pluto has a moon, Charon.

Together, the more than 50 moons of the outer solar system provide a rich choice of targets for exciting scientific exploration. Some of their representative characteristics (as far as we now know them) are listed below.

Jupiter's Moons: The Galilean Satellites

IO

- radius: 1,816 ± 5 kilometers
- density: 3.55 grams/cubic centimeter
- active volcanoes
- internally heated by tidal forces from Jupiter and Europa
- molten silicate interior
- sulfur and frozen sulfur dioxide on surface

EUROPA

- radius: 1,563 ± 10 kilometers
- density: 3.04 grams/cubic centimeter
- rocky interior
- ice crust (≤100 kilometers), *possibly* covering a global water ocean
- global fracture patterns
- relatively young surface with almost no craters

GANYMEDE

- radius: 2,638 ± 10 kilometers (largest in the solar system)
- density: 1.93 grams/cubic centimeter
- only 20 to 30 percent smaller than Mars
- water or ice mantle
- ice crust (≤75 kilometers)
- young grooved terrain with intricate fractures
- old dark cratered areas
- fresh craters expose ice

CALLISTO

- radius: 2,410 ± 10 kilometers
- density: 1.81 grams/cubic centimeter
- ice/rock crust
- water or ice mantle
- large-scale topography diminished by ice flow
- fresh craters expose ice
- older cratered surface with huge, ringed "basins"

Saturn's Moons

TITAN

- equatorial radius: 2,560 kilometers
- density: 1.92 grams/cubic centimeter
- only satellite with dense atmosphere
- atmosphere predominantly nitrogen and methane
- atmospheric pressure at surface = 1.5 atmospheres
- possible existence of ethane oceans on surface
- large variety of organic compounds being formed in the atmosphere
- rocky core
- water ice mantle

ENCELADUS

- radius: 250 kilometers
- density: 1.16 ±0.55 grams/cubic centimeter
- most reflective body in solar system
- surface is relatively smooth
- long grooves dominate smooth areas of surface
- may be internally active, but source of energy for activity remains a puzzle
- apparently the source of particles for the E-ring

IAPETUS

- radius: 720 kilometers
- density: 1.16 ±0.09 grams/cubic centimeter
- leading hemisphere is darker than trailing hemisphere, with very low albedo
- lighter hemisphere cratered
- cause of darker hemisphere is unknown; both internal and external processes have been postulated

TETHYS

- radius: 525 kilometers
- density: 1.21 ±0.16 grams/cubic centimeter
- appears to be made of almost pure ice
- surface is scarred by a huge trench (Ithaca Chasma) extending from the north pole down to the neighborhood of the south pole
- contains large crater with a well-developed central peak

Uranus' Moons

MIRANDA

- radius: 250 kilometers
- density: 2.0 grams/cubic centimeter
- innermost satellite
- internal structure and composition uncertain
- surface a "patchwork" of unexplained geologic structures: valleys, cliffs, and highly organized grooved terrain

ARIEL

- radius: 600 kilometers
- density: 1.3 ± 0.5 grams/cubic centimeter
- occupies orbit between Miranda and Umbriel
- existence of broad, branching, smooth-floored valleys strong evidence for liquids flowing over the surface
- brightest of the uranian moons
- cratered terrain along with valleys and fault scarps dominate the surface

TITANIA

- radius: 800 kilometers
- density: 2.7 ± 0.7 grams/cubic centimeter
- rocky interior overlaid by thin ice crust
- surface a combination of cratered terrain and trenches, scarps, and subsidence features

Neptune's Moon

TRITON

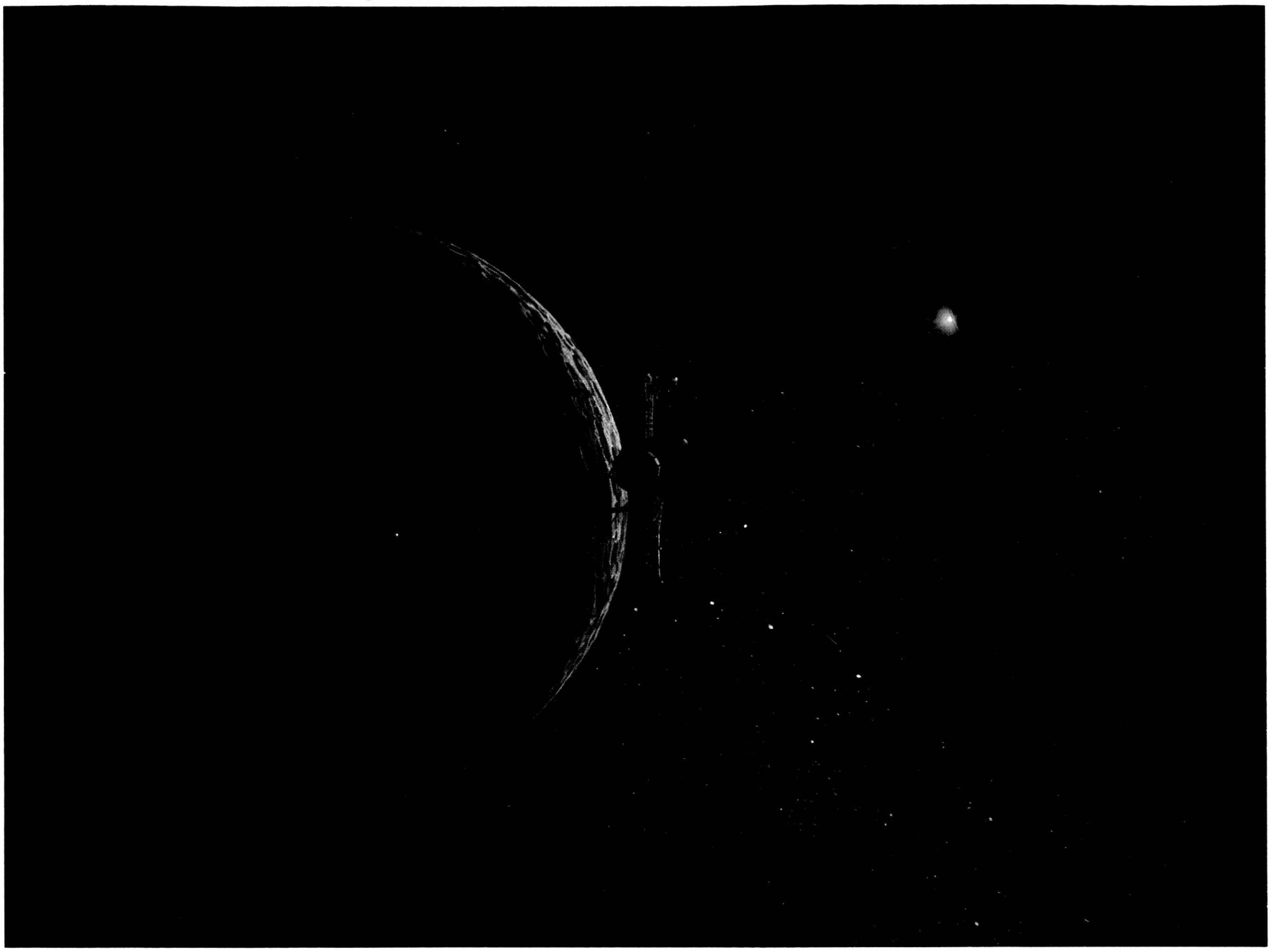
- radius: 1,750 ± 250 kilometers
- density: 2 to 4 grams/cubic centimeter
- density estimates are uncertain since there is no other satellite close enough to Triton to observe perturbative effects
- orbits Neptune in retrograde motion
- may possess ocean of liquid nitrogen on its surface
- possible existence of methane atmosphere

Pluto's Moon

CHARON

- radius: 20 to 30 percent that of Pluto?
- density: not known
- large size of Charon in relation to Pluto makes this pair a "double planetary system" similar to Earth-Moon system on a smaller scale

A future space probe passes Pluto and its large moon, Charon.



engines would also allow the spacecraft to "hover" above the rings in a forced small-circle orbit. The instrument complement on a "ring rover" could include remote sensors to determine the composition of ring particles, as well as detectors to determine the nature of local magnetic fields and their associated charged particles.

TITAN

This large and remarkable satellite of Saturn, with its dense shroud of haze, its nitrogen-rich atmosphere, and its possible hydrocarbon oceans, is a prime target for Augmentation Missions in the outer solar system. Two high priorities for the proposed *Cassini* mission are the direct analysis of Titan's atmosphere with a deployed probe and the radar mapping of its still-hidden surface from the orbiter spacecraft. Such information will be essential to design a future buoyant (or floating) station for a major Titan mission.

The *Cassini* results will make Titan a much better-known world, but there will still be major unsolved problems: Titan's atmospheric

structure and dynamics, the nature and composition of its surface, and its internal structure, including such features as seismicity and heat flow.

One major objective that will certainly remain after the *Cassini* mission is to determine the nature of the organic material that has accumulated on Titan's surface during perhaps the last 4½ billion years. An attractive next step in the post-*Cassini* exploration of Titan would therefore be a mission that could sample and analyze material scooped from Titan's solid surface or skimmed from the shores and surfaces of possible bodies of liquid hydrocarbons.

A second group of objectives for future Titan missions is centered on the significance of Titan as a prototype for the other icy, volatile-bearing bodies in the solar system. How were the gases in Titan's atmosphere originally incorporated in the ices that formed the satellite? Was this mixture of gases determined by general conditions in the outer part of the original solar nebula, or did it reflect special local conditions created by the formation of Saturn in the vicinity? What is the relationship of Titan's present atmosphere to the atmospheres recently identified on Pluto and on Neptune's moon Triton, and to the gases expelled from comets when they approach the Sun? What is the relationship, in both composition and original source, between the atmospheres of Titan and related worlds, and the volatiles of Earth?

Both of these goals are addressed by one mission already studied, in a preliminary way, as a possibility for Titan–a buoyant station which would be deployed in Titan's atmosphere. This device would be a kind of powered dirigible capable both of exploring the atmosphere of Titan and of analyzing the surface with an instrument package lowered on a long tether. The specific mission concept includes an orbiter to serve as a communications relay and to carry out its own scientific observations. The mission could also include optional instrument packages deployed by sounding rockets or penetrators.

This ambitious concept is only one of several possible means for the intensive exploration of Titan. Other methods could involve simpler, non-mobile soft landers, which might in turn deploy sounding balloons. These landers could carry a large complement of instruments like those on the Mars *Viking Landers*. The landers could be provided with flotation capability, if it does turn out that the surface of Titan is covered by oceans of liquid hydrocarbons. The latter situation also suggests the possibility of exploration of Titan's surface by a boat-like lander.

TRITON

This largest satellite of Neptune has already captured considerable attention because recent ground-based studies have established the existence of an atmosphere, the presence of methane on its surface, and the possibility that the moon may be covered in part by oceans of liquid nitrogen.

A Closer Look at Titan

Titan, Saturn's largest moon, is a unique and exciting target for future planetary exploration. Unlike any other moon, Titan has a thick atmosphere, composed chiefly of nitrogen and methane. Within this atmosphere, a complex process of chemical evolution has occurred and continues to occur.

One aspect of this atmospheric chemical evolution is especially exciting, for it may be repeating some of the earliest steps in the processes that led to the appearance of life on Earth. In Titan's atmosphere, complex organic molecules are being produced from simpler molecules (such as methane) by the effects of solar ultraviolet light and the bombardment of the atmosphere by energetic electrons from Saturn's radiation belts. These organic molecules then accumulate on Titan's surface as solids or liquids, while the hydrogen released in the reaction escapes to space from the top of Titan's atmosphere. Titan is therefore a

Clouds and lakes of ethane dominate this artist's conception of Titan's bizarre surface.

large natural laboratory in which we can study, on a planetary scale, some of the processes that may have led to the origin of life on Earth.

Titan's thick and murky atmosphere completely hides its surface from view, and there is little direct evidence of what the surface is like. Some speculations about the surface can be made from our knowledge of the *Voyager* measurements of the properties of Titan and from comparisons with the large moons of Jupiter. Titan's low density suggests that it is composed chiefly of water ice, and ice may therefore be the major component of Titan's surface. If it is, then high topographic relief should be absent because of the tendency of ice to flow; the surface of Titan may resemble the surfaces of the other icy moons Callisto and Ganymede.

Large impact craters may be rare on Titan; ice flow and atmospheric erosion would tend to destroy the original crater shapes. In addition, Titan's surface has probably been shaped by internal activity, as has clearly occurred on Saturn's nearby moons Dione and Rhea.

Whatever the general geologic character of Titan's surface, it must be covered with organic materials, precipitated as fine particles *(aerosols)* by the chemical reactions taking place in the atmosphere. Over geologic time, estimates suggest that a layer as thick as 500 meters may have been built up. Since ethane is likely to be the dominant organic material produced in the atmosphere, it has been suggested that this ethane has collected to form a global ocean perhaps a kilometer deep. Alternatively, there may be hydrocarbons scattered over the surface.

There must surely be some kind of geologic activity on Titan. The methane that is consumed by the photochemical reactions in the atmosphere must be constantly replaced, or the chemical reactions would have stopped long ago. One possibility is that "volcanic" activity on Titan releases methane from Titan's interior to the surface, where it can be stored in oceans or lakes of liquid methane or ethane.

The *Cassini* mission, which will release a probe into Titan's atmosphere and will sense its surface with radar, is expected to replace these speculations with a wealth of fact. The mission will: (1) determine the structure and chemical composition of Titan's atmosphere; (2) determine the exchange and deposition of energy within the atmosphere; (3) locally characterize the surface morphology of Titan. The *Cassini* mission will produce the first determinations of the following issues:

- What is the chemical composition of Titan's aerosol layers?
- What are the details of Titan's atmospheric structure and dynamics?
- What are the actual reactions for chemical synthesis in Titan's atmosphere?
- What are the reasons for the hemispheric asymmetry in Titan's atmosphere?
- What is the nature and composition of Titan's surface, and what are its surface winds?
- What is the temperature profile in Titan's atmosphere, and what processes control it?
- What was the nature of the original solar nebula in the region near Titan?

Following *Cassini,* even more detailed questions about the atmosphere will be formulated for answer by a subsequent mission of the Augmentation class, which will certainly require new technologies to allow extended measurements on the surface of Titan, measurements that will address questions related to the surface and interior of this remarkable moon.

A "ring rover" travels above Saturn's ring plane before descending to investigate the particles that comprise the ring system.

The future exploration of Triton will strongly complement the exploration of the planet Pluto. Both worlds are very similar: small, cold, and with significant amounts of outgassed volatiles. They offer important clues about original conditions on the outermost fringes of the original solar nebula. The two worlds also offer some intriguing dynamical comparisons; they may not, in fact, have always been where they are now. Pluto was once suspected of being an escaped satellite of Neptune. (The recent discovery that Pluto has a moon of its own, named Charon, has weakened but not entirely destroyed this theory.) Neptune's own moon Triton currently revolves around Neptune in a retrograde orbit that should be short-lived by geologic standards; Triton may in fact break up or crash into Neptune in as little as a few million years.

Future exploration of Triton could logically follow the missions developed for Titan. An initial mission could be a Neptune orbiter capable of carrying out global radar mapping and spectroscopic measurements of Triton. Subsequent missions could involve possibilities already discussed for Titan: a buoyant station or soft landers, perhaps preceded or supplemented by a penetrator network.

Summary

The outer planets and their varied satellites play a critical role in our attempts to understand the nature, origin, and evolution of the solar system. Because of their complexity, their distance, their extreme thermal and radiation environments, and the diversity of possible investigations, the worlds of the outer solar system also present major scientific and technical challenges for the remainder of this century and for the early years of the next.

The Core Program (plus the results of the *Voyager*, *Galileo*, and the possible *Cassini* missions) will provide fundamental increases in our knowledge about the outer planets. These missions will carry out the reconnaissance of Uranus and Neptune. They will provide long-term remote observations of Jupiter, Saturn, and their moons. In keeping with the concept that *in situ* atmospheric analyses (which are analogous to sample returns from solid bodies) should be the general goal for study of the outer planets, these missions will provide atmospheric data for Jupiter, Saturn, Titan, and Uranus, allowing detailed comparisons to be made between these different worlds.

Even after the outstanding accomplishments of current missions and of the Core Program Missions, there will remain an abundance of critically important scientific questions. Exploration, even at the level made possible by the Core Program, is severely hampered by an incomplete data base, by long travel times, and by severe planetary environments. The Core Program will still leave major gaps in our understanding, especially in the cases of Neptune and Pluto.

Detailed consideration and selection of possible Augmentation Missions to the outer planets must await the return of data from

missions now in progress and planned for the near future. However, examples of desirable Augmentation Missions can be identified now. Potential targets include Jupiter, Io and the other Galilean satellites, Titan, Saturn's rings, and Triton. Possible Augmentation Missions should be studied now in more detail in order to identify specific requirements for necessary technology development. These studies can be modified as more data are obtained from future mission activities.

Titan is an especially interesting target for future exploration, even though detailed information from the proposed *Cassini* mission will be required for the planning and final selection of an Augmentation Mission. One possible mission is a long-lived atmospheric dirigible with a capability for surface analysis. Other mission possibilities for other worlds include a Saturn "ring rover," deep atmospheric probes to the planets, and penetrators, landers, and surface rovers for such satellites as Io.

Progress beyond the Core Program requires major technological developments. The primary need is for improved propulsion capabilities beyond those available from the *Shuttle/Centaur* combination. Additional technologies required for the spacecraft and instruments include robotics for autonomous operations, radiation-hardened components, and high- and low-temperature components.

Among the various possibilities for improved propulsion capabilities, the development of nuclear-electric propulsion (NEP) could be particularly important, especially for missions in which significant orbital changes are desired. An early development of NEP would have an important effect on planning for both Core Program and Augmentation Missions. NEP would make it possible to launch larger missions to Neptune and Pluto, to send combined orbiter/probe missions to Uranus and Neptune, to carry out large missions to Jupiter and Saturn, and to carry out major orbital plane changes essential for such missions as a Saturn "ring rover" or a Jupiter orbiter focused on magnetospheric studies.

During the first years of the Space Age, while the worlds near Earth–the Moon, Mars, and Venus–became familiar places, the worlds of the outer solar system remained largely unknown. Only during the last few years have the *Pioneer* and *Voyager* missions revealed the full strangeness, the grandeur, and the unexpected diversity of the planets and moons that lie beyond the asteroids.

We now look to the outer solar system with a mixture of emotions–anticipation to see the faces of still-unknown moons and planets, excitement at the potential for even greater scientific discovery on worlds we have still seen only in brief flybys. The obstacles between us and the outer solar system are formidable–great distances, long travel times, extreme planetary environments, and an incomplete base of information. But the knowledge that awaits us on these distant worlds is tremendous, and without it our understanding of the solar system can never be complete.

We are not barred from the outer solar system; we are only challenged. We need new data and new tools, and we should start

now to acquire them, so that our plans can go forward. We can use the last years of the 20th Century to build a solid framework for the decades of exciting discovery and scientific exploration that can be done in the early years of the 21st.

CONCLUSIONS

1. The worlds of the outer solar system, especially the gas giants like Jupiter and Saturn, can provide unique insights into important and unanswered scientific questions: the formation of the solar system and the universe itself; the nature of pre-biotic organic chemistry; the origin and dynamics of planetary ring systems; and the nature of planetary magnetospheres and high-intensity charged-particle behavior in them. The varied moons of the outer planets, many of them virtually unknown, also display a wide range of planetary processes and time scales ranging from primordial cratering on icy worlds to present-day active volcanism.

2. In contrast to the terrestrial planets and small bodies, for which the desired long-term exploration method is the collection and return of samples to Earth, the exploration goal for the outer planets is the *in situ* analysis of their atmospheres by atmospheric probes, a technique that will be first applied in the *Galileo* mission to Jupiter.

3. The greatest problem in identifying and selecting Augmentation Missions to the outer planets is the incompleteness of the present data base, which will not be significantly improved until the early 1990s, after the *Voyager* encounters of Uranus and Neptune, the *Galileo* mission to Jupiter, and the use of the *Hubble Space Telescope* for observations of such outer planets as Neptune and Pluto.

4. The outer planet missions of the Core Program, planned for the 1990s, will accomplish some major scientific achievements and will provide an important additional data base, especially for Saturn, Titan, and Uranus.

5. The combination of a currently incomplete data base and a large number of scientifically exciting possible missions makes it impossible, *at this time,* to select a single mission, or a single class of missions, as the highest-priority Augmentation Mission to the outer planets.

6. Despite the presently incomplete data base, a number of exciting possible Augmentation Missions can be identified now as worthy of future detailed study: deep atmospheric probes, hard landers and penetrator networks on satellites, long-term magnetospheric studies, balloons or surface landers, and long-term, close-up observations of ring systems. Possible targets for such missions include Jupiter, Io and similar satellites, Saturn's rings, Titan, and Neptune's moon Triton.

7. Major technological developments are essential to undertake most Augmentation Missions to the outer planets. The most urgent need is for improved propulsion capability, combined with aerocapture techniques. (These technologies are also essential for the *Mars Sample Return* and *Comet Nucleus Sample Return* missions.) Other technological needs include: new communications techniques, radiation-hardened components, autonomous robotics, balloon technology, low-temperature components, and high-temperature components.

RECOMMENDATIONS

1. The outer planet missions in the planned Core Program should be carried out as expeditiously as possible to expand the existing data base to the point where Augmentation Missions to the outer planets can be seriously discussed, evaluated, and planned in detail.

2. A *Neptune Flyby/Probe* and a *Pluto Flyby* mission must clearly be added as soon as possible to provide consistency with the planned Core Program. Even though it is recognized that these missions will probably not be launched before 2000, they are essential to raise Neptune and Pluto to the same level of understanding (the *Reconnaissance* level) as the other planets of the outer solar system.

3. The possibility of combining two outer planet missions in the recommended Core Program (the *Saturn Orbiter* and the *Titan Probe)* into a joint NASA-ESA mission called *Cassini* should continue to be studied in detail and should be implemented if possible. Such a combination has two advantages: it would accelerate the Core Program by combining two separate missions into a single launch, and it would establish a means for international cooperation in exploring the outer solar system.

4. The possibilities for future international cooperation in other missions of the recommended Core Program should continue to be examined in detail as the Core Program progresses and evolves.

5. If more capable propulsion techniques, perhaps combined with aerocapture capabilities, are available by the year 2000, a logical and essential augmentation of the Core Program should be the undertaking of orbiter or orbiter/probe missions to Uranus, Neptune, and Pluto, in order to bring these planets to the same level of understanding (the *Exploration* level) as the other planets of the solar system.

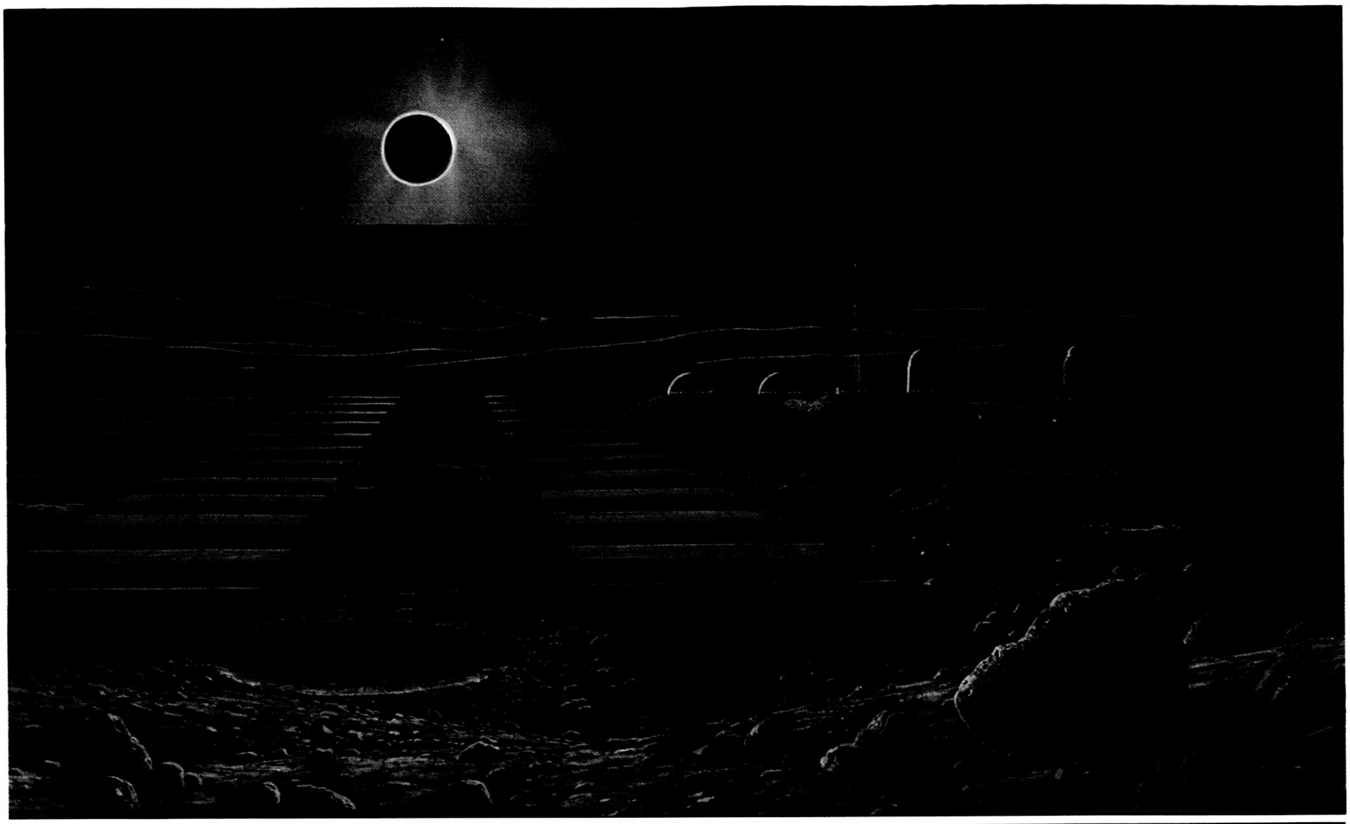
6. More detailed studies of possible Augmentation Missions should be undertaken at once in order to identify in more detail their scientific and technical requirements. These studies should be modified and updated as new data are received from current missions *(Voyager, Galileo)* and future Core Program Missions, e.g., *Cassini.*

7. Titan is an especially interesting target, and special attention should be given to its intensive exploration, even though data from the proposed *Cassini* mission are essential for planning an Augmentation Mission in detail. One possibility for Titan is an atmospheric dirigible (a buoyant station) with a capability for surface analysis as well as atmospheric measurements.

8. Required major technological developments should be undertaken in the near future in order to make possible the implementation of major Augmentation Missions to the outer planets in the years after 2000. Improved propulsion capabilities are essential and might be met by development of solar-electric propulsion and nuclear-electric propulsion.

9. Because of the critical importance of improved propulsion and aerocapture capabilities to outer planet Augmentation Missions, such missions should be immediately studied in sufficient detail so that their requirements can be taken into account while implementing technological developments needed for the sample return Augmentation Missions.

A lunar base during eclipse.
As Earth passes between the Sun and Moon, a shadow falls on the Moon. Earthbound observers see a lunar eclipse; lunar observers see a solar eclipse.



6. The Riches of Space

NEAR-EARTH RESOURCES: THEIR EXPLORATION AND USE

The Need for Space Resources

Use of near-Earth space for profit-making activities is no longer a subject for the distant future. The space environment is being used now for economic activities. Communications satellites are an important part of our industrial growth. Commercial sales of the first space-fabricated commodity (latex microspheres) have started, and the processing of pharmaceuticals and biological compounds in microgravity is on the verge of becoming another commercial activity.

The recent national commitment to establish an orbiting Space Station in the 1990s has spurred plans for increased human habitation of space by the early years of the next century. Any such establishment will clearly need large amounts of materials in Earth orbit–structural modules for habitation, oxygen for life support and propulsion, and bulk matter for shielding from cosmic rays and other radiation.

Where will these materials come from? They can come from Earth–if we are willing to continue to pay the heavy transportation costs in fuel required to lift materials from Earth's surface. There is

another choice–to use the materials provided by other bodies in space, just as we are now economically using the space environment itself for economic activities.

The cost of energy to overcome Earth's gravitational field and to punch through its thick atmosphere makes any Earth-based space transportation system inherently inefficient. When the *Space Shuttle* is launched, only about 1.5 percent of its launch mass is actual payload. Most of the remainder (over 80 percent) is fuel to make the trip from Earth's surface to low-Earth orbit (LEO, about 300 to 500 kilometers up).

Gravitationally, the Moon is a far more efficient source of materials. Given the lower lunar gravity (only one sixth that of Earth), the lack of a lunar atmosphere, and the possibility of decelerating by aerobraking through Earth's atmosphere in going from the lunar surface down to LEO, it is likely that overall payload efficiency from the Moon's surface to LEO could exceed 50 percent. Travel from a near-Earth asteroid to LEO might be energetically even more efficient because there is virtually no gravitational field to overcome at launch. Savings for transport from the Moon or an asteroid to geostationary orbit (GEO, 35,880 kilometers up) would be even greater.

The potential for saving most of the present energy costs of transporting materials to LEO and GEO is a strong incentive for considering in detail how we might use nonterrestrial materials. It is quite possible that, for certain uses, the extensive front-end costs of establishing lunar or asteroidal mining and launch facilities could be repaid in the long run by the significantly lower transportation costs.

Several potential uses of nonterrestrial resources in near-Earth space have already been identified. The simplest is the use of unprocessed bulk material as shielding for astronauts and for communications or military satellites. For example, the shielding necessary to protect six astronauts (or an equivalent volume of sensitive electronic gear) from solar flares (a major problem both in GEO and on the lunar surface) would weigh at least 85 metric tons, about three current *Space Shuttle* payloads. An equivalent mass of lunar soil *(regolith)* or asteroidal material could serve the same purpose. If demands develop for large amounts of shielding in space, then the use of lunar or asteroidal materials could become economic.

One possible product of lunar materials, oxygen, could provide an early economic return for use as propellants in the Space Transportation System (STS). Once the planned Space Station is established at LEO in the early 1990s, there will be extensive traffic between LEO and GEO, chiefly to deploy communications satellites at GEO or to retrieve them for repair. For this traffic, development of an Orbital Transfer Vehicle (OTV) is being considered.

Assuming that the OTV uses conventional hydrogen/oxygen propulsion, current traffic projections indicate that about 300 tons of oxygen will be required annually by the year 2000. That amount of oxygen would require ten *Space Shuttle* flights to LEO each year, carrying oxygen alone. At this level of consumption, an economic return for obtaining lunar oxygen for the OTV becomes plausible,

and, if lunar oxygen were readily available, additional activities in space could raise the demand by as much as a factor of ten. Permanently shadowed craters at the lunar poles may contain permanent deposits of water ice. Such lunar deposits, as well as near-Earth asteroids–especially carbonaceous ones–offer the additional possibility of obtaining hydrogen as well as oxygen.

Longer-term economic uses of lunar or asteroidal materials would be tied to future major space activities in Earth orbit or on the Moon itself. In these situations, nonterrestrial feedstocks could be processed to provide metals, ceramics, and glasses for buildings, machinery, communication lines, and other structures. Oxygen, a major component of both lunar and asteroidal rocks, would be used as a propellant in rocket motors and for life-support systems. Metals are potentially available for a number of uses: solar cell panels (silicon), structural members (iron, aluminum, and titanium), and electrical conductors (aluminum, iron). Nonterrestrial materials could also be processed to produce glasses, ceramics, and foams, while unprocessed raw materials could be used in bulk for radiation shielding. Lunar water, if present, and carbonaceous asteroids could supply hydrogen, oxygen, and water for propellants, life support, and chemical processing. In an ideal space-based economy, only a relatively small amount of material would be required from Earth, including: volatiles (hydrogen), hydrocarbons (plastics, sealers, solvents), special metals (copper, zinc, germanium, molybdenum) for alloying and other purposes, and equipment for mining and processing.

Locations of Available Nonterrestrial Resources

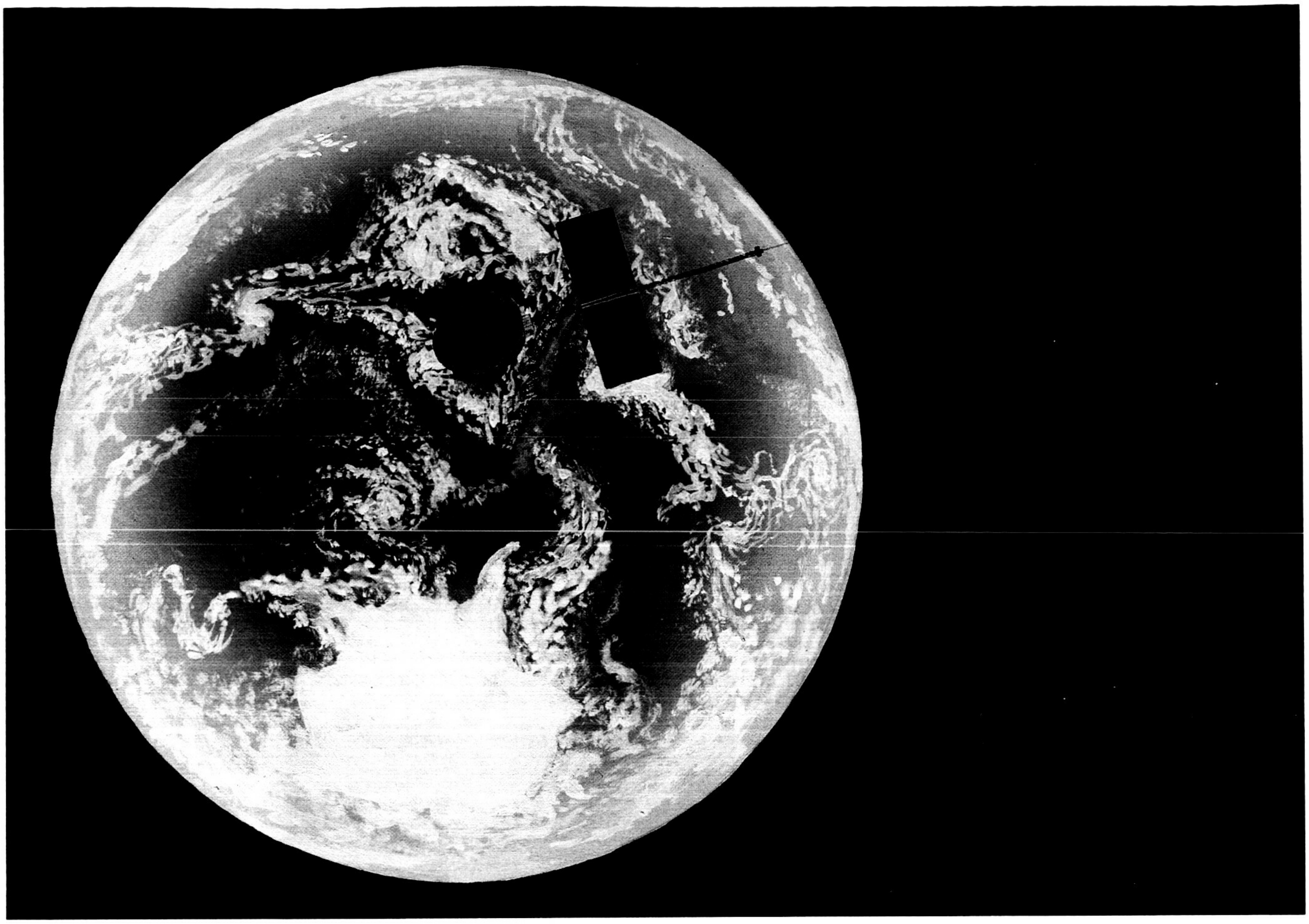
For the immediate future, nonterrestrial resources are restricted to bodies that: (1) are easily accessible from Earth; (2) have gravity fields weak enough for easy removal of material from their surfaces. The two most-discussed possibilities are the Moon and the Earth-crossing asteroids.

THE MOON

From a resource standpoint, the Moon has the advantages that it is nearby, has frequent launch windows, and can be reached in a few days' time. At present the Moon is the only nearby body whose surface state and composition we know in some detail. More than 90 percent of the Moon has been photographed. Orbital surveys by the *Apollo* missions have provided gross surface chemical data for about a quarter of its surface and have also provided some geophysical data (such as gravity and magnetism). The samples returned from nine sites on the Moon's nearside (six *Apollo*, three U.S.S.R. *Luna*) and at least three lunar meteorites discovered on the Antarctic ice cap are providing extensive information about the Moon's chemistry, history, and evolution.

Despite the large amount of lunar information available, there are still serious gaps in our knowledge, some of which must be remedied before the resource potential of the Moon can be accurately evaluated.

Bringing an asteroid back home.
The asteroid will become a new moon, and its metals and other raw materials will be mined for the benefit of Earth's people and global economy.



Photographic and chemical surveys are incomplete for the lunar farside and are either poor or entirely lacking for the polar regions. Sample sites are restricted to the equatorial region of the Moon's nearside; we have no sample data for much of the nearside, the entire farside, or the polar regions. The lack of polar information is particularly serious, because deep polar craters, never warmed by sunlight, could contain permanently trapped water or carbonaceous materials that would be essential contributions to a lunar resources economy.

Except for their lack of volatiles, especially water, the available moon rocks are basically Earthlike. They are composed of the same chemical elements and (with minor exceptions) of the same minerals as are terrestrial rocks. There are two general types of moon rocks. Dark-colored basalt lavas cover the flat, low *maria* on the Earth-facing side. Except for some minor chemical differences (such as the absence of water and other volatiles), the lunar lavas are similar to terrestrial ones. Lighter-colored crystalline rocks, of the gabbro and anorthosite families, make up the rugged lunar highlands that cover 80 percent of the Moon. With some minor chemical differences, they too are similar to terrestrial analogues found in ancient continental shield areas and in large differentiated igneous bodies.

The actual surface material of the Moon is not solid bedrock; it is a layer (usually tens to hundreds of meters thick) of fine powdery rubble (the *regolith* or lunar soil) that has been formed by the destruction of the underlying bedrock by meteorite impact over billions of years. Because the Moon has no atmosphere, even tiny cosmic particles strike its surface at high velocities. These impacts shatter, melt, and mix the bedrock together. The resulting lunar soil appears to cover the entire Moon, except for rare steep regions like the walls of Hadley Rille (visited by the *Apollo 15* mission), where solid lunar bedrock is exposed.

The lunar soil is crucial to considerations of lunar mining because it is so accessible; it is probably the only easily accessible lunar material. It is chemically similar to the underlying lunar bedrock from which most of it is derived. The lunar soil also contains about one to two percent of meteoritic debris as well as a few percent of exotic rock types transported in from other regions of the Moon. These components do not change the bulk composition greatly.

As a raw material, the lunar soil has the advantage of having already been finely crushed (the median grain size of its particles is about ten microns or 0.01 millimeter), and it can therefore be easily excavated and transported. Physically, it may prove more difficult to manipulate and process. So much of it is fine-grained and cohesive that it has been described as "a black talcum powder with rocks in it."

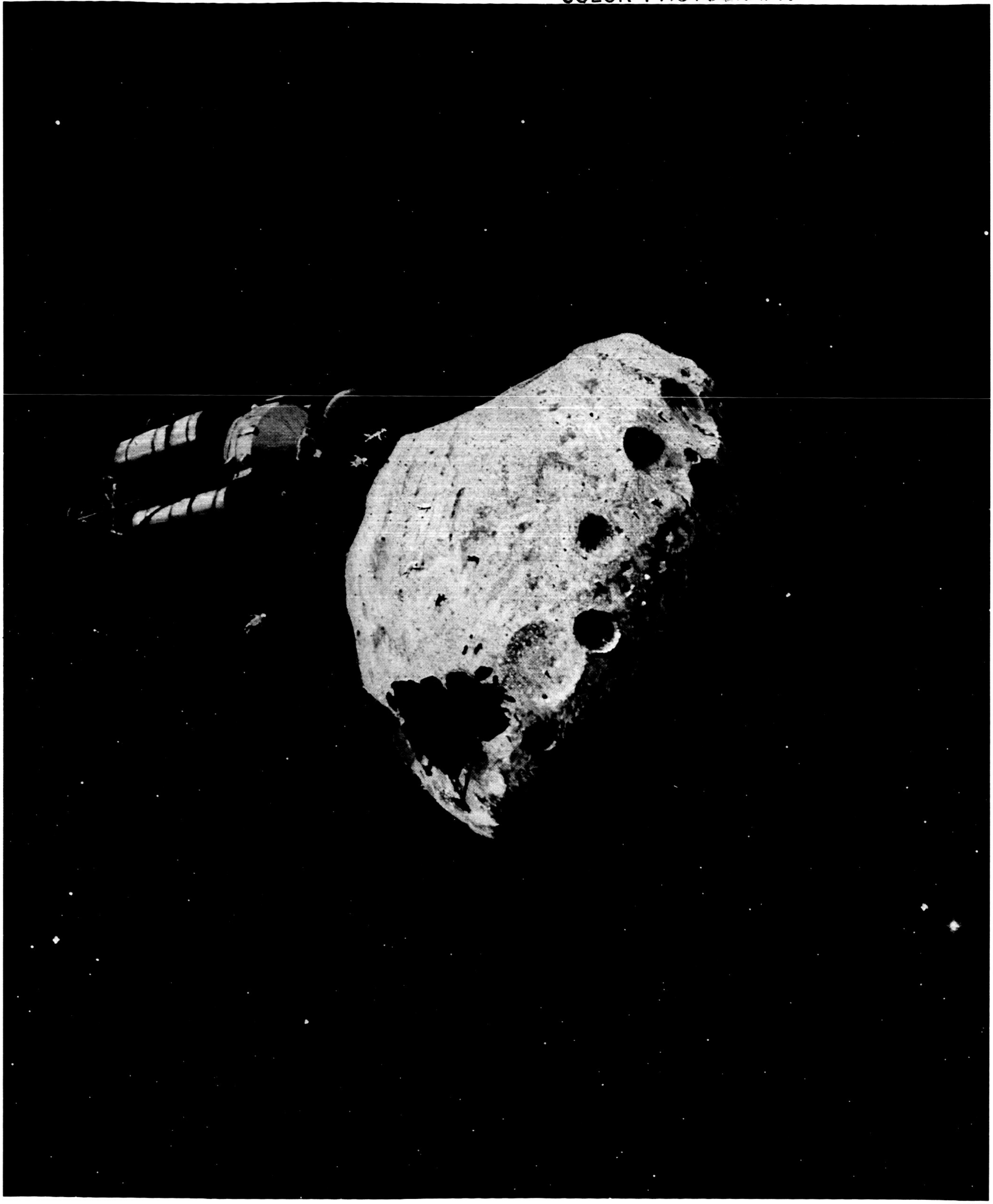
The mass of material available on the Moon is more than adequate to support any anticipated human activity in space. A pit only one kilometer square and ten meters deep in the lunar soil (a very modest excavation by terrestrial standards) can supply more than 15 million tons of lunar material. (It would take about 500,000 *Space Shuttle* missions to carry that amount of material from Earth to LEO.)

ASTEROIDS

Several thousand asteroids are known, and hundreds of millions are believed to exist. The largest known asteroid is Ceres, which is 700 kilometers in diameter (about the size of Texas). Most known asteroids are a few tens of kilometers in diameter, and it is believed that there exists a large and undiscovered population of asteroids with diameters of 100 meters to one kilometer.

Asteroids in the Main Belt, with orbits between Mars and Jupiter, are difficult to reach from Earth for two reasons: (1) the large energy difference between their orbits and Earth's orbit, which requires significant propulsion capability and fuel consumption; (2) the long travel times (on the order of several years) required for round-trip missions. For these reasons, special attention is being given to families of asteroids (the Apollo, Aten, and Amor groups) whose orbits cross or approach the orbit of Earth. These objects are energetically more accessible, in general, than the Main Belt asteroids. Energy costs to reach some "Earth-crossers" from Earth are comparable to those involved in going from Earth to the Moon.

More than 40 Earth-crossing asteroids have already been discovered. (Icarus, which came within 7 million kilometers of Earth in 1968 on its way to a close approach to the Sun, is a well-known example.) The entire Earth-crosser population is probably much



Reconnaissance of an Apollo asteroid. A future exploration vessel "parks" beside a small Earth-approaching asteroid, and astronauts float across to conduct close-up studies. During this first contact with a world beyond the Moon, the distorted shadow makes a ghostly afterimage of the Apollo *landing module that first brought humans to the Moon. In the far distance, lower right, Earth and the Moon make a bright double star.*

larger; statistical studies suggest that as many as 1,000 Earth-crossers more than one kilometer in diameter may exist, and there may be as many as 100,000 with diameters of 100 meters to one kilometer. Even small asteroids can be large sources of material. An asteroid one kilometer in diameter contains about 2 billion tons of material; even an object as little as 100 meters in diameter may contain as much as 2 million tons. Some of the materials may be in a pulverized state, like the lunar regolith; other material may be solid.

Asteroid missions and mining operations will have special complications. The long trip times require more complex spacecraft as well as advances in closed life-support systems. Furthermore, the negligible gravity fields of asteroids will require the development of zero-gravity mining and processing techniques. (It has been suggested that one way to avoid some of these problems would be to transport small asteroids to near-Earth space for the actual mining operations.)

Chemical Composition of Available Resources

THE MOON

The chemical composition of the Moon is grossly bimodal. The dark basalt lavas have abundant titanium, magnesium, and iron. The most common kinds of highland rocks are rich in calcium and aluminum. Minor variations are found (e.g., high- and low-titanium basalt lavas). However, the chemical compositions appear to be uniform over sufficiently large areas of the Moon, so that many sites offering a given type of material are available.

ASTEROIDS

The materials that make up asteroids are almost totally unknown. No samples have yet been returned from any known asteroid, nor has any spacecraft made close-up studies, by remote sensing or other methods, of any asteroid. We do not yet know whether some or all asteroids, like the Moon, are covered with a layer of fragmental rubble, nor how thick such a layer might be.

There are, however, two sources of indirect evidence about asteroid compositions: (1) meteorites that fall to Earth, which are believed to be derived from objects in the asteroid belt; (2) ground-based telescopic multispectral measurements of individual asteroids, from which some broad and general conclusions can be drawn.

Both lines of evidence indicate that asteroids are composed of materials that are far more diverse than the surface materials of the Moon. Most meteorites (and therefore, we think, most asteroids) are composed largely of silicate minerals and glasses similar to those that make up lunar and terrestrial rocks. They are not, however, identical. Meteorites are richer in minerals containing iron and magnesium and have more iron metal–in some cases, as much as or more than a few percent. Most meteorites also contain only minor amounts of aluminum-bearing minerals.

Two unusual varieties of meteorites, which occur only as a few percent of recovered falls, have attracted particular attention:

(1) ***Iron meteorites*** are actually chunks of iron-nickel alloy. They are predominantly iron (about 90 percent by weight), nickel (five to ten percent), and cobalt (0.6 percent), with trace amounts of other elements, including gold and platinum group metals (0.001 to 0.01 percent). Such objects are potential sources of large amounts of metals. A metal asteroid one kilometer in diameter (if such a thing exists) could be worth more than $1 trillion at current market prices.

(2) ***Carbonaceous meteorites*** are composed chiefly of silicate and oxide minerals. They are notable for their high contents of carbon (as much as three to four percent) and water (several percent, most of which is probably combined in silicate minerals). Although these meteorites are uncommon (only about four percent of known falls), they are of special interest because they indicate a possible asteroidal source for critical volatiles (carbon, hydrogen, and water) that may not be present in sufficient amounts on the Moon.

Nonterrestrial Ores and Their Processing

GENERAL PROBLEMS AND CONDITIONS

The chemical elements in both lunar and asteroidal materials have many potential uses in space. Furthermore, the masses available on the lunar surface, and in even small asteroids, are adequate to support any possible space activities for the indefinite future.

However, the mere existence of potential resources does not mean that they can (or will) be economically used. Two conditions must be met in order for a mineral deposit (e.g., a pile of lunar soil or a small asteroid) to become an ore (i.e., an economic resource). The conditions are: (1) the deposit must contain a high enough concentration of one or more valuable elements; (2) it must be possible to extract and use those elements in economically advantageous ways. Whether any mineral deposit becomes an ore depends not only on its geology, chemistry, and tonnages, but also on outside factors such as engineering, technology, economics, and social conditions. These factors change with time, and the history of terrestrial mining has shown that today's waste rock frequently becomes tomorrow's ore.

The greatest concern about being able to use nonterrestrial resources in the future is that little of our terrestrial mining and extraction experience may be directly relevant to space operations. There are two reasons for this:

1. Terrestrial and nonterrestrial ore deposits are fundamentally different.

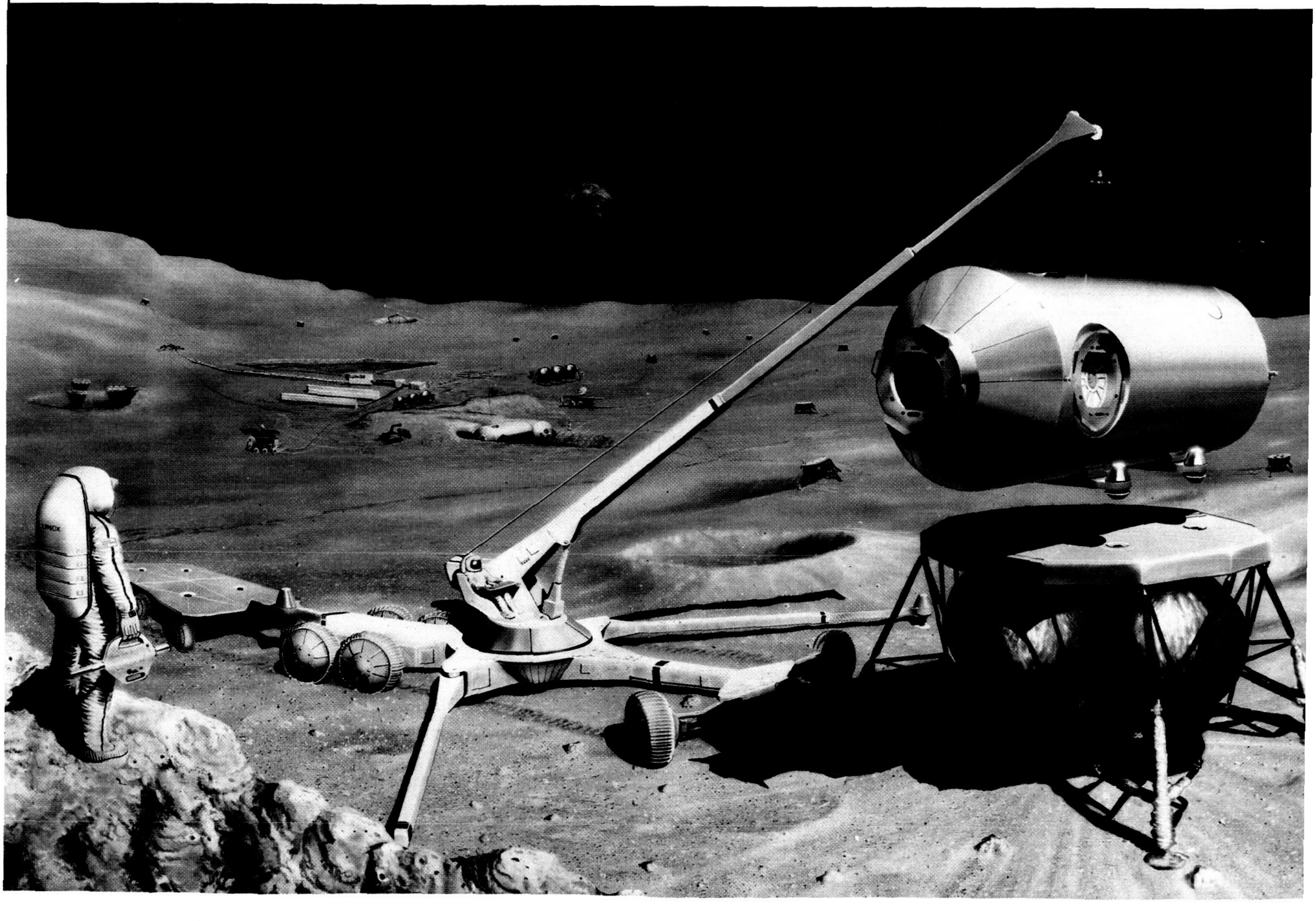
Terrestrial mining operations do not use ordinary soils and rocks. On Earth, virtually all ore deposits are the result of unique geologic processes that concentrate critical elements far above their usual (and uneconomic) abundances (usually parts per million) in the crust. The most common terrestrial enrichment processes involve water (both on Earth's surface and within its crust), and some involve life.

A Mining Prospectus for the Moon

Many essential products for large-scale space activities can be provided from the Moon: bulk lunar soil for shielding, silicon, aluminum, iron, titanium, glasses, and ceramics. The raw material, lunar soil, exists as a thick layer everywhere on the Moon, already crushed and ready to be dug up and processed.

Details on the composition of lunar materials at two lunar sites are given below. The *Apollo 11* site, on the lunar maria, provides soil that is high in iron and titanium. The *Apollo 16* site, in the lunar highlands, provides soil richer in calcium and aluminum. Also included are the amounts (in tons) of different chemical elements that could be mined from a small pit only 100 meters square and ten meters deep. (Lunar soil compositions are from S.R. Taylor (1982), *Planetary Science: A Lunar Perspective,* Lunar and Planetary Institute, Houston, TX, Table 4.3a, p. 140.)

At an interim lunar base, site for future lunar mining operations, a lunar crane unloads one of the last habitation modules for the base.



Lunar Maria (Basalt Lavas) (*Apollo 11* Site)

	Weight Percent as Oxides		Weight Percent as Elements		Tons from Small Pit
Silicon (Si)	SiO_2	41.3	Si	19.3	38,600
Titanium (Ti)	TiO_2	7.5	Ti	4.5	9,000
Aluminum (Al)	Al_2O_3	13.7	Al	7.3	14,600
Iron (Fe)	FeO	15.8	Fe	12.3	24,600
Magnesium (Mg)	MgO	8.0	Mg	4.8	9,600
Calcium (Ca)	CaO	12.5	Ca	8.9	17,800
Sodium (Na)	Na_2O	0.41	Na	0.30	600
Potassium (K)	K_2O	0.14	K	0.12	240
Manganese (Mn)	MnO	0.21	Mn	0.16	320
Chromium (Cr)	Cr_2O_3	0.29	Cr	0.14	280
Oxygen (O)	---	---	O	42.2	84,400
TOTAL		**99.9**		**100.0**	**200,000**

Lunar Highlands (Anorthosites) (*Apollo 16* Site)

	Weight Percent as Oxides		Weight Percent as Elements		Tons from Small Pit
Silicon (Si)	SiO_2	45.0	Si	21.0	42,000
Titanium (Ti)	TiO_2	0.29	Ti	0.17	340
Aluminum (Al)	Al_2O_3	29.2	Al	15.5	31,000
Iron (Fe)	FeO	4.2	Fe	3.3	6,600
Magnesium (Mg)	MgO	3.9	Mg	2.4	4,800
Calcium (Ca)	CaO	17.6	Ca	12.6	25,200
Sodium (Na)	Na_2O	0.43	Na	0.32	640
Potassium (K)	K_2O	0.06	K	0.05	100
Manganese (Mn)	MnO	0.06	Mn	0.05	100
Chromium (Cr)	Cr_2O_3	0.08	Cr	0.04	80
Oxygen (O)	---	---	O	44.6	89,100
TOTAL		**100.8**		**100.0**	**200,000**

In sharp contrast to Earth, there is no evidence that the same concentration processes occur on the Moon or asteroids. Nonterrestrial "ores" will probably consist of common lunar or asteroidal rock or of the mixed rock materials found in the surface regolith. Compositions of these materials can be uniform over large areas. Although there is no current evidence for major deposits of normally rare elements on the Moon, extreme concentrations of some elements have been found in a few lunar rocks, so a wider variety of ores may actually be present. However, we do not have any data at this time that would justify the development of any processing technologies or procedures based on the availability of such concentrations.

*2. **Technology for mining and extracting elements from terrestrial ores will not be directly applicable to nonterrestrial materials or to the nonterrestrial environment.***

The problems of extracting chemical elements from typical terrestrial rocks (basalt lavas, granites, or other crystalline rocks) are so severe that such deposits do not compete economically with the rarer but more enriched ones. These problems include the difficulty of physically separating one or more economic minerals from the others that make up the rock, as well as the frequent occurrence in the rock of undesirable elements that interfere with the extraction processes. A special problem in extracting the chemical elements themselves is that the chemical bonds in the silicate and oxide minerals that make up most common rocks are very strong and require much energy to break.

For these reasons, there are virtually no smelting operations on Earth that process bedrock to obtain useful refined materials. In a few small operations, basalt lavas have been processed in bulk for casting and ceramic manufacture. There have also been studies on the possible extraction of aluminum from anorthosite (a crystalline high-aluminum rock similar to rocks from the lunar highlands).

Another problem is that all terrestrial mining and extraction technology is designed for terrestrial conditions which include: (1) a high gravity field; (2) available air, water, and fossil fuels; (3) the existence of an atmosphere or water bodies as sinks for waste heat or unwanted by-products. None of these conditions apply in space.

It is clear that successful mining and processing of nonterrestrial resources requires the development of unique technologies that do not now exist and which must be specifically developed to meet the following unique conditions:

(1) Vacuum: There is no atmosphere to retain volatile materials or to serve as a convenient sink for waste heat developed during processing.

(2) Low gravity or microgravity: Separation processes which require a gravity field (e.g., density separations) could be retarded or completely nullified. Even the transfer of materials from one place in the extraction system to another will require special arrangements.

*(3) **Uniform feedstocks:*** No locally enriched deposits are known to exist, and the source materials can have a uniform composition over wide areas. This situation has compensations as well as drawbacks. New technologies must be designed, but they can be confidently based on continuously uniform feedstocks. In addition, the availability of similar materials over wide areas of the Moon will reduce problems involving mining claims because there will probably be no economic reason to compete for a single small area. (The possible identification of sources of lunar ores is discussed in more detail later in this chapter.)

*(4) **No water or other volatiles:*** Most terrestrial extraction procedures require large amounts of water, and there is no need for stringent conservation. On the Moon, water and other volatiles may need to be imported. If so, they must be carefully retained and recycled by both processing and life-support systems. This problem is especially severe for the Moon, but it exists for all objects except perhaps for the carbonaceous asteroids.

*(5) **Lack of hydrocarbons:*** Hydrocarbon- and carbon-based fuels, reducing agents, and reagents will not be locally available. Alternate energy sources (especially solar power) will be required. A second problem is that all necessary hydrocarbons (plastics, solvents, etc.) must be imported.

*(6) **Different day/night cycles:*** On the Moon, each day and night is two Earth-weeks long. This condition will generate unique problems such as the thermal control of exposed equipment, possible thermal shock during the day/night transition, scheduling of mining and processing activities, and the unavailability of solar power for half the time. For asteroids, rotation rates and the resulting day/night periods are poorly known; they may range from hours to days for smaller objects.

THE LUNAR SOIL

Although in a gross sense a sample of lunar soil is chemically uniform, it is not actually chemically or physically homogeneous. Both the lunar soil and its parent bedrock are composed (like Earth rocks) mainly of small crystals (minerals) that are chemical compounds formed by the combination of metal elements with oxygen. These minerals are of two principal types: (1) silicates in which various metals (calcium, iron, aluminum, magnesium) are combined with networks of oxygen and silicon atoms; (2) oxides in which metals (iron and titanium) are combined directly with oxygen atoms. The lunar soil also contains some glassy derivatives of these minerals and small quantities (0.1 to 1 percent) of free iron metal and iron sulfides. These substances occur as small particles derived both from lunar bedrock and from impacting meteorites. This metal also contains significant amounts of nickel and cobalt.

The most common components of lunar soil are minerals (and glasses) made of silicates. The most common minerals are *pyroxene* (a calcium-aluminum silicate), *olivine* (an iron-magnesium silicate), *feldspar* (a calcium-aluminum silicate also called anorthite or plagioclase), and *ilmenite* (an iron-titanium oxide). Very minor amounts of *silica* (a group of silicon-oxygen minerals) and silica-rich

Orbital Debris: The Deadly Litter

The first economic use of lunar material in space may be to protect us from a consequence of our own success. Our space achievements have produced a slowly growing cloud of man-made debris around Earth. This debris is a potential hazard to a permanent Space Station, to the *Space Shuttle* that will service it, and to large spacecraft left in orbit for long periods of time. We may need to shield our future space structures from this hazard, and we may find it practical to bring lunar materials down to Earth orbit to provide the shielding.

We now track more than 5600 man-made objects in orbit around Earth. Of these, 72 percent are classified as debris. That category does not include dead satellites, but refers to spent rocket stages, ejected satellite shrouds, clamps, pieces from exploded fuel tanks, insulation, and various odds and ends left by astronauts. In addition to these relatively large objects, we estimate that there are tens of thousands of pieces of untracked debris the size of marbles, and literally billions of tiny paint flakes orbiting Earth.

Most of this material is potentially lethal. Even a tiny metal chip, half a millimeter across, can puncture a space suit and injure an astronaut. Larger objects, one to ten millimeters in size, can damage or destroy spacecraft. Pitted windows on the *Space Shuttle* and tiny craters peppering the returned *Solar Maximum Mission (SMM)* satellite indicate that the hazard posed by this debris is already significant.

The probability of a collision with debris increases with the size of the object we place in orbit. The larger the object–spacecraft, astronaut, or *Space Shuttle*–the more likely it is to be hit. The Space Station will be larger than anything placed in space before, and it will therefore be more likely to be hit.

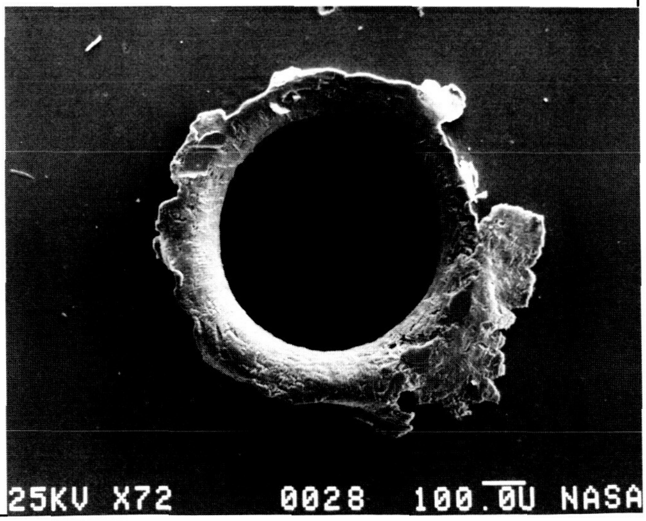
Given the infinite dimensions of outer space, it seems strange to worry about collisions between objects. But most past and future space activity is concentrated in low-altitude orbits, 250 to 1,000 kilometers up, and it is in this region where the debris has been left. In the geosynchronous orbit used for communications satellites, 35,800 kilometers up, debris is not a problem.

Debris close to Earth will reenter the atmosphere and burn up, but even at low altitudes, gravitational forces take a long time to pull debris out of orbit. A bit of debris in orbit 1,200 kilometers up may remain in space for as long as 300 years.

The amount of debris is continually increasing, and the more there is, the greater are the chances that orbiting satellites or spacecraft will suffer seriously damaging collisions. We already have evidence that damage to the *Space Shuttle* and several satellites was caused by orbiting debris, most probably undetected clouds of paint chips.

As the situation becomes worse, we may have to provide massive shielding for space installations to protect them from orbiting debris. Because the energy required to lift mass from Earth's surface to low-Earth orbit is so high (costing about $1,000/pound), it may prove economical, for large future space structures that require great amounts of shielding, to obtain the necessary mass from the Moon. The cost, in energy, of carrying material from the lunar surface to low-Earth orbit is much lower. Lunar soil could be used for shielding with no more processing than is needed to put it into some kind of space-age sandbag. Bulk lunar soil would also provide good shielding for humans and machines from cosmic rays and radiations released in solar flares, as well as from space debris.

Impact pit, more than half a millimeter across, formed on the* Solar Maximum Mission *satellite by an orbiting paint chip.



glasses also occur. These different materials occur in the lunar soil mainly as very fine particles. While the regolith does contain boulders, cobbles, and chips, the average grain size of that portion of the lunar soil which passes through a one-millimeter sieve is only about 0.005 to 0.01 millimeters.

Most of the particles in the lunar soil are complex ones composed of mixed glass and mineral fragments. These particles, called *agglutinates*, are produced by the melting and mixing caused by meteorite impacts. Agglutinates are frequently porous. Embedded in them are small quantities of gas trapped from the solar wind. The small size and irregular shape of these agglutinate particles are largely responsible for the strongly adhesive and cohesive character of the lunar soil.

Because individual particles in a lunar soil have chemical compositions that vary more widely than does that of the bulk soil itself, it may be possible to obtain several chemically different feedstocks by processing a lunar soil to separate out and concentrate particular components. A feldspar-rich concentrate would have a higher proportion of calcium and aluminum than would a bulk soil. Similarly, an ilmenite-rich concentrate from a basalt lava would be an improved source of iron and titanium. The traces of iron metal in the soil might be directly concentrated by magnetic methods or other techniques. Agglutinate particles might be concentrated as a source of volatile materials, although their content of solar wind gases is relatively small.

On the basis of chemical composition and available tonnages, lunar materials could form the basis of an extensive manufacturing technology. What is now lacking is the new technology needed to extract the essential chemical elements, together with the space-based economic conditions that would make their extraction profitable.

Despite the lack of established technology for processing lunar soil and related materials, there have been several workshops and small-scale studies which indicate the potential and provide both encouragement and indications for future research. Concepts and techniques are gradually being established for obtaining several products from lunar materials:

1. ***Glass and ceramic products*** can be produced by the fusion of lunar rocks, soils, or silicate mineral concentrates. This is one of the few areas in which any comparable terrestrial technology exists; basaltic lavas are melted and cast to make sewer pipe in Eastern Europe.

2. ***Oxygen***, not available as a free element on the Moon, is the major component of lunar materials. It has already been experimentally released from silicate minerals by several techniques, including direct electrolysis and fluoride separation. If the reaction is carried out by a process involving initial hydrogen, then water may be obtained as a product. This water can then be electrolyzed into hydrogen and oxygen. Water and oxygen have been experimentally obtained in such a way by using hydrogen to reduce the ferrous iron in the mineral ilmenite to iron metal. The hydrogen can

be recycled, so that the net process yields oxygen gas plus iron metal.

Fluoride separation methods provide an alternative to electrolysis and hydrogen reduction to extract free oxygen and metals from lunar rocks and soil. In such methods, the highly reactive element fluorine (introduced either as a gas or as such compounds as hydrofluoric acid) is used to break apart the tightly-bound oxygen and metal atoms that make up most minerals and rocks. These techniques have long been used on a small scale to extract oxygen from terrestrial minerals and rocks for scientific analyses.

3. ***Aluminum*** forms up to 18 percent by weight of the feldspar-rich rocks of the lunar highlands. These rocks also contain as much as 20 percent silicon and 46 percent oxygen, and they can readily be mined for all three elements. It is unlikely that a better source for aluminum will be found in near-Earth space. Such rock (anorthosite) has been seriously considered in Norway as a feedstock for commercial production of aluminum. Soils such as those sampled at the *Apollo 16* site near North Ray Crater (15 percent aluminum) would be an especially promising feedstock to use.

The terrestrial process for extracting aluminum involves leaching of aluminum oxide from the ore into a hot sodium hydroxide solution, followed by precipitation of the oxide, mixing of the oxide with the expendable mineral cryolite, melting, and electrolysis. This method does not seem adaptable for use on the Moon or in an orbiting smelter. Fluoride extraction may be a feasible alternative process for extracting aluminum in space.

4. ***Iron*** is present as metallic particles, mostly as iron-nickel alloys, in concentrations of a fraction of a percent in all lunar soils. This iron is easily extracted with a hand magnet. The magnetic fraction also contains glassy agglutinate fragments which have incorporated metallic iron. The glassy material would have to be separated out before the iron could be processed into steel.

Lavas from the lunar maria are also rich in iron (up to 17 percent). Preliminary experiments suggest that the iron can be separated by melting and electrolysis. Solar energy could supply the necessary heat and current. The fluoride extraction scheme could also yield iron.

5. ***Titanium*** exceeds seven percent in some lavas. It is also possible that the denser titanium-bearing minerals have accumulated into even richer ores as the lavas solidified. Electrostatic precipitation in air has been used in small-scale experiments to separate ilmenite from other basaltic minerals. This technique may be applicable to titanium-rich soils from the lunar maria. Titanium has also been separated as an alloy from a melt of lunar lava composition by electrolysis.

6. ***Silicon*** comprises as much as 21 percent by weight of most lunar rocks and soils. It can be separated by the fluoride extraction method, and it has also been extracted as an alloy by electrolysis of molten simulated lunar basalt.

7. ***Volatiles*** (carbon, hydrogen, water, nitrogen, noble gases, etc.) could be collected from the lunar soil, where they occur in low concentrations implanted by the solar wind. Such extractions have

Space Resources: Unanswered Questions

Despite the potential for using near-Earth resources in future space activities, we must answer many questions before we can use them. To get the answers, we must explore the Moon (and asteroids) more thoroughly, and carry out a variety of laboratory investigations and economic and social studies about future space activities and their costs. Before we decide whether or how to use near-Earth resources, we must get definite answers to the following questions:

Resource Assessment

- Are there permanent deposits of water and ice in shadowed craters in the Moon's polar regions?
- Are there regions of the Moon that contain rock types different from any collected by the *Apollo* missions?
- How can finely powdered material like lunar soil be excavated, manipulated, and transported?
- Can the small amount of iron metal in lunar soil be extracted by simple processes like magnetic separation?
- Can the solar wind gases trapped in the lunar soil be efficiently extracted? Can significant amounts of hydrogen be obtained in this way?
- How many near-Earth asteroids are there? How accessible are they?
- What are the compositions of near-Earth asteroids? Does this population contain any of the especially interesting metallic or carbonaceous varieties?
- How closely can the compositions of known meteorites be matched with known asteroids?
- What is the nature of the surface layer on asteroids? Is it solid bedrock or broken fragmental material?

Extraction and Processing Technology

- What are the best methods of processing lunar soils to form bulk products like glasses and ceramics?
- What is the best technique for extracting oxygen from lunar soils–hydrogen reduction, electrolysis, fluoride separation, or something else?
- What new technologies could be developed to take advantage of the special conditions on the lunar surface (vacuum, solar energy, cold)? Can electrostatic separations or solar-furnace heating be used?

Space Technology

- How can the requirements for asteroid mining (long trips, long stay times, zero-gravity operations) best be met?
- What requirements must be met by the Space Station and its related infrastructure to support the assessment and use of near-Earth resources in the future?
- What are the specific requirements for a lunar mining base, and how can they be met?

Market Research

- What is the foreseeable demand for large amounts of material, for example, bulk shielding and oxygen for propellants, in near-Earth orbit for the next ten, 20, or 50 years?
- What is the foreseeable demand for large-scale structures (solar power stations or huge communications arrays) in space? What materials, in what quantities, would be required for them?

already been carried out by simple fusion methods in connection with scientific studies of the lunar soil. Initial heating of lunar feedstocks, before further processing, could drive off significant amounts of hydrogen (75 parts per million), nitrogen (120 parts per million), and carbon (200 parts per million).

THE SEARCH FOR LUNAR ORES

Our existing lunar data base demonstrates that the lunar soil can provide abundant supplies of several major elements–oxygen, silicon, iron, titanium, magnesium, and calcium. But there are extensive gaps in our data base. We have samples from only nine sites, all on the nearside. Our orbital measurements of the surface chemistry cover less than a third of the lunar surface.

Viewed by themselves, these simple facts sum up an amazing human achievement. But when looked at from the viewpoint of future resources use, the available data are scant and limited. Nine sampling sites constitute a very incomplete survey of a world whose surface area is roughly equal to that of North and South America combined. The orbital measurements have a very low ground resolution, and the values for many chemical elements are not accurate enough to draw detailed conclusions about specific regions of the Moon.

In fact, we have not mapped the Moon adequately enough to determine the spatial distributions of even the common rock types, and we remain ignorant of the full variety of materials that the Moon can provide. It is essential that we determine definitely whether water is present and available at the lunar poles, as has been suggested. We need to determine the general surface compositions over the entire Moon. And we need to search for areas where critical chemical elements may have been concentrated by strictly lunar processes.

Even though the Moon lacks water and life to concentrate chemical elements, other mechanisms could have operated to produce enrichments. One possible mechanism is the settling of dense mineral crystals in large bodies of molten lava to form enriched layers and pods in the resulting rocks, a process frequently observed on Earth. Many lunar lavas contain dense oxide minerals (ilmenite and chromium-rich spinels) that could accumulate under appropriate conditions into concentrated ore bodies.

Another possible concentration mechanism on the Moon is the vaporization of relatively volatile elements (such as sulfur, the halogens, lead, zinc, cadmium, arsenic, silver, and antimony) either during volcanism (especially with fire-fountain activity) or by meteorite impact. These elements have already been observed to be considerably concentrated in surface coatings on some lunar *breccias*. (Lunar breccias are fragmental rocks consisting of pieces of a variety of older rocks; these breccias are formed by meteorite impacts.) Some *Apollo 16* rocks actually rusted quickly when returned to Earth. They contained condensates of iron chloride (the mineral *lawrenceite*) that reacted with the water and oxygen in the atmospheres of both the spacecraft and Earth.

Other lunar samples provide small-scale evidence for different concentration mechanisms that are still not well-understood. In some lunar rocks, microscopic injected veins of once-molten iron sulfide are observed; such sulfides could be enriched in copper, zinc, and other elements. Small fragments found in many lunar breccias are enriched more than 50-fold in rare-earth elements, phosphorus, thorium, uranium, barium, potassium, and other trace elements.

Remote sensing of the lunar surface, both from lunar-orbiting spacecraft and from telescopes on Earth's surface, is essential to a better characterization of lunar resource potentials. Such studies have already provided valuable information, especially when the orbital data could be combined with information from samples returned from the same locations that were measured from orbit. As a result, we know that the aluminum-rich mineral feldspar is common in rocks from the lunar highlands, especially the regions sampled by the later *Apollo* missions. Similarly, some lavas collected from the lunar maria are rich in titanium, and Earth-based infrared telescopic observations, using the *Apollo* samples as controls, have identified regions of the maria which have this type of lava at the surface.

The lunar samples also show a wide proportionality between their contents of thorium and uranium and those of other chemical elements (e.g., phosphorus, potassium, rare earths, zirconium, barium, hafnium) that are trace constituents of lunar rocks. The orbiting gamma-ray experiment carried on several *Apollo* missions measured actual thorium concentrations in lunar surface materials, detecting the highest readings in the Mare Imbrium–Oceanus Procellarum region. Thus, we have a good idea where to explore in detail for enrichments of thorium-correlated trace elements.

The *Apollo* orbiting experiments determined the surface chemical compositions by detecting the characteristic X-rays and gamma rays emitted to space by the lunar surface. These measurements yielded estimated surface concentrations for silicon, magnesium, and aluminum that were averaged over regions of 400 or more square kilometers (X-ray) and for thorium, iron, potassium, and titanium averaged over regions of 2,500 or more square kilometers (gamma ray). Such spatial coverage is far too wide to detect specific small ore bodies; moreover, the precision of the chemical measurements was limited by low detector resolution. Earth-based telescopic infrared spectra are obtained with spatial resolution of a few kilometers on nearside regions of the Moon that are distant from the limbs. Such spectra record the presence of iron in the minerals pyroxene and olivine.

To improve our lunar data base to the point where the next step in decisions about lunar resources will become possible, we must map the rest of the Moon's surface with increased spatial resolution by using a battery of instruments: improved X-ray and gamma-ray detectors, combined with multispectral scanning, high-resolution spectral images of selected areas, and medium-resolution imaging. Such studies will yield important scientific results as well as critical

information about resources. In fact, many major lunar science goals are addressed by the proposed *Lunar Geoscience Orbiter (LGO)* mission in the Core Program. This mission would provide a comprehensive overview of the Moon's compositional trends and would have the capability of detecting significant amounts of water near the surface in the permanently shadowed floors of polar craters.

Remote sensing observations from orbit may not be adequate to discover usable lunar ores for such critical minor elements as chromium, manganese, phosphorus, sulfur, or nickel, or for trace constituents such as copper, zinc, or chlorine. Until the capability exists to make detailed analytical traverses (manned or automated) on the lunar surface, the possibilities for such ores must be assessed indirectly by combining the data from lunar samples, orbital experiments, and theories about possible lunar ore-forming processes. This process is a continual one; new data are continually being gathered, and our theories are consequently in a state of constant evolution.

Until more direct lunar sampling can be done, the best strategy for estimating whether enriched lunar ores of any kind exist appears to be fourfold: (1) continue basic petrological and geochemical characterization of the complex lunar breccias and soils of the *Apollo* collection; (2) continue studies of terrestrial analogues of lunar rocks in order to understand better the mechanisms that are responsible for both the similarities and differences between lunar and terrestrial rocks; (3) continue theoretical and experimental studies to provide insight into the processes that form both lunar and analogous terrestrial rocks; (4) obtain global lunar geochemical data from the *Lunar Geoscience Orbiter* mission, so that we can accurately extrapolate the lunar sample data to the different compositional provinces of the lunar surface. Terrestrial strategies for mineral exploration have been guided to a significant extent by how we think geochemical differentiation processes work on Earth. We should accumulate a large enough lunar data base to make this approach applicable to the Moon as well.

ASTEROIDS

We know much less about the asteroids than we do about the Moon, and it is therefore harder to plan for the eventual use of asteroids as resources in space. In contrast to the Moon, for which there exist returned samples and chemical data over much of its surface, current information about asteroids is scantier, more general, and more uncertain. As far as asteroids are concerned, there is much to be done just to find out exactly what materials are out there before we can plan the details of how to use them.

The first step toward the eventual use of asteroidal resources must be to increase our information for at least a few asteroids (especially Earth-crossers) to the level of our current understanding about the Moon. There will be many steps in this process, and the first steps can be designed now and taken in the near future.

- We need to continue and expand ground-based sky surveys to locate more Earth-crossing asteroids, so that we can develop a better understanding of this critical group of objects: their number, orbits, accessibility, and chemical composition.

- Beyond this, we need to plan now a mission to survey one of these objects at close range. The *Near-Earth Asteroid Rendezvous (NEAR)* mission, which was included in the proposed Core Program (under the name *Earth-Approaching Asteroid Rendezvous)* because of its fundamental scientific importance, will also provide critical data about the chemical and physical character of one target asteroid, information that is essential to plan the mining and processing of such objects. Because of its importance for both science and resource assessment, the *NEAR* mission should be undertaken as soon as possible following the *Lunar Geoscience Orbiter (LGO).*

- In the more distant future, when definite asteroids have been identified for possible resource use, sample return missions will almost certainly be needed to identify, characterize, and study their material in detail. The main purpose of such a mission will be to support resource development in space, but, like all sample return missions, it will also provide unique and fundamental science gains as well.

- Current ground-based research relevant to the characterization and processing of asteroidal materials should continue to be supported, even though plans for the eventual use of such resources are in an early state of development. Meteorite research, already established as an important part of space science, will also continue to provide information about the character and diversity of available asteroidal resources.

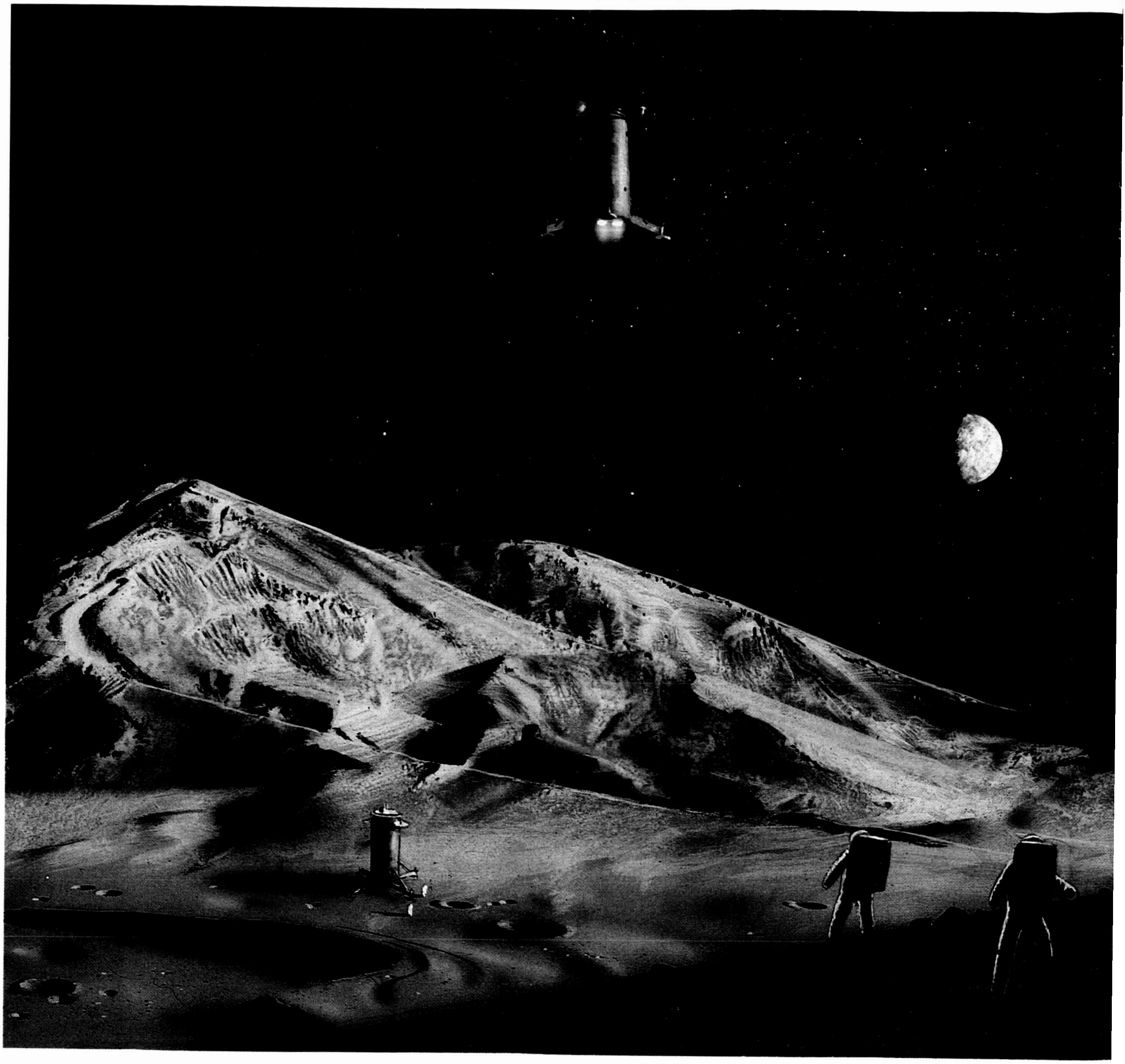
- Meteorites, and their synthetic analogues, can also be used to test possible methods for extracting essential materials (water, oxygen, and metals). Extraction methods developed for lunar rocks and soil may also be applied to stony meteorites, which are composed of similar minerals. More exotic meteorites–metal-rich and carbonaceous ones, in particular–will require special techniques. Iron meteorites, despite their potential value, will require special processing methods to overcome their hardness, toughness, and durability.

Infrastructure and Supporting Technology

An extensive operating infrastructure in space will be needed to extract and use nonterrestrial resources. Components of this infrastructure must include transportation, habitation, power, and communications, all of which are challenging, and none of which is now in place.

If all the needed space infrastructure had to be developed solely to enable the early use of nonterrestrial resources, it is unlikely that such resources would become economic very soon. However,

*A future generation of Earth-Moon vehicles delivers astronauts and supplies on the first post-*Apollo *lunar expedition.*



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many of the components are being developed for other purposes, especially for the planned Space Station, and plans for using nonterrestrial resources can be based on a larger infrastructure than now exists.

The space-based infrastructure already envisioned to be in place by the mid-1990s includes: (1) the *Space Shuttle* to provide transport from Earth's surface to LEO; (2) the Space Station in LEO as a point for fueling, servicing, and staging; (3) an Orbital Transfer Vehicle (OTV) to carry payloads from LEO to GEO. Space Station capabilities available by the end of this century could include: (1) launch, recovery, and servicing of space-based OTVs (including extensive propellant transfer and storage); (2) managing and tending free-flying subsatellites; (3) building large space structures.

Manned bases on the Moon or on asteroids are in a sense also space stations, and they can draw to a large extent on the technology now being developed for the LEO Space Station. **A major challenge for the immediate future is to ensure that the various elements of the Space Station and the rest of this infrastructure are planned and established in ways that can support the eventual use of non-terrestrial resources.** The fact that many of the necessary technical developments are already under way lends an air of urgency to the need for studies of resource assessment and processing technology, because the results of these studies will be an important input for technical decisions to be made in the near future.

TRANSPORTATION

Lunar or asteroidal mining will require the capabilities to perform several transportation steps: (1) from LEO (or GEO) to lunar (or asteroidal) orbit; (2) from lunar orbit to the lunar surface and vice versa; (3) from lunar (or asteroidal) orbit to LEO or GEO.

For the first step, an Orbital Transfer Vehicle (OTV) that can reach GEO from LEO can, with little additional propellant, either enter lunar orbit or rendezvous with certain Earth-crossing asteroids. Current studies of OTV development should keep in mind the potential gains in science and resource exploration to be made by adding this relatively minor additional capability.

For the second step, a unique reusable lunar/asteroidal lander will also be required. The general character of such vehicles could develop from the technological base established for the OTV, but additional studies and developments will be required to address requirements specific to the Moon or to asteroids.

To complete the return trip, aerocapture technology needs to be developed to enable return to LEO from GEO or from the lunar surface. For aerocapture, it may be possible to obtain much higher transportation efficiencies by constructing ablative heat shields from lunar-derived ceramics. For moving bulk material from the Moon to Earth orbit, a lunar-based mass driver (an electromagnetically-powered launcher) may be more effective than propellant-driven vehicles.

HABITATION
Early lunar or asteroidal habitations can most likely be based on Space Station modules, which are planned to include the necessary command/control stations, living and recreation areas, and health maintenance facilities. Minor modifications will probably be needed to ensure that equipment developed for microgravity (e.g., fluid circulation systems) can operate in the lunar one-sixth gravity.

POWER
A minimum power estimate for lunar mining can be based on the need to obtain 300 tons of oxygen per year for use as propellants at LEO. This power has been estimated at less than one megawatt, a value which is well within the range of both photovoltaic and nuclear power sources currently under consideration.

SURFACE OPERATIONS
Mining operations on the surface of the Moon or on an asteroid present unique technological challenges that are not covered by current planning. Operations on the lunar surface will require adaptation to an absolutely dry and dusty environment in which electrostatic effects are more pronounced than in terrestrial environments. Considerable automation of operations, involving at least the use of teleoperated mining equipment in the early stages, will be required. Earth-based automation and teleoperation techniques are already developing rapidly, and similar automation for spacecraft should be in operation in 15 years. Robotic techniques for mining and processing lunar or asteroidal regolith should evolve as natural extensions of current state-of-the-art methods.

Movement of personnel and materials on the lunar surface also presents special problems, and the solutions will involve significant extensions of current technology: advanced self-contained roving vehicles, ballistic launchers, and possibly impulse devices like the mass driver. For work in the microgravity environment of asteroids, an advanced "Manned Maneuvering Unit," like that proposed for transportation between the Space Station and nearby satellites (a few kilometers away) would be required. Much of the technology base for some of these systems will be available in the near future, but special attention must be paid to systems which have specific needs generated by the lunar or asteroidal environments in which they must work.

COMMUNICATIONS
Interestingly, communications requirements for nonterrestrial resources do not demand new technologies but do require additional capabilities. Such communications use communications satellites in GEO or the 12-hour orbiting Global Positioning Satellites, because these devices are "Earth-looking" and not designed for communications from above them. Furthermore, the Earth-based tracking system once used for the *Apollo* program is being dismantled. The future use of lunar or asteroidal resources will require, and will probably promote, the development of new communications capabilities. Such capabilities do not necessarily require new technology and might be provided in several ways. Two

or three GEO satellites, capable of looking outward, might be ample. Alternatively, ground-based stations such as those currently used to support deep-space missions could be used, but new stations dedicated to support of the lunar base, or of an asteroidal mission, would probably be required. On the Moon itself, operations at the lunar poles or on the lunar farside would require relays because line-of-sight communication to Earth would not be possible. Possible relay techniques include lunar-orbiting relay satellites or the laying of relay lines (either wire or optical fiber) across the lunar surface to nearside stations.

To Build a Foundation

There is no question that, in principle, nonterrestrial resources can provide essential support to the major space projects of the future. The universe contains no fundamental barrier to the use of such resources; they can be reached, mined, processed, and used. The problems to be solved involve the technical ones of transportation, mining, extraction, and construction, together with the establishment of social and economic conditions that will make the use of such materials economical.

Large-scale use of nonterrestrial resources in sufficient quantities to justify the needed major front-end developments in transportation, mining, and processing, will require the establishment of major human enterprises in space. Discussions of what form these developments might take, and of how and when they might come about, are beyond the scope of this report. However, the SSEC has been able to indicate some areas where more information is needed and to describe some efforts that can begin to provide it.

The actual use of nonterrestrial resources in space may be in the more distant future, but the decision to use them must be made much sooner because of the large-scale developments required. The question, "Can we use extraterrestrial resources in space?" must therefore be answered in the near future, and it is essential to begin to collect information now, so that, when the question is asked, it can be answered on the basis of accurate information about uses, techniques, costs, and schedules.

A better understanding of potential resources on the Moon and on asteroids is essential, and this resource assessment can go forward hand-in-hand with the future scientific exploration of these objects. Two missions already included as candidates in the Core Program–*LGO* and *NEAR*–can provide a valuable science yield together with the essential chemical and physical information needed to develop the details of future mining and processing operations.

We already know enough about potential nonterrestrial resources to know that our current terrestrial mining and extraction techniques are totally inadequate for use in space, and the immediate development of new methods is essential. Our data about nonterrestrial materials–especially lunar soils–are already sufficient to begin this task and to test, on a small scale, the methods that we develop. The best strategy for seeking economic methods for

Helium-3 From the Moon: An Exciting Energy Source Possibility

Development of practical *fusion technology* has long been sought as the future hope for efficient and abundant energy production on Earth. The public attractiveness of this energy option depends to a large extent on its ability to guarantee a nuclear-safe process with minimum maintenance cost, radioactive waste, and thermal pollution. The lunar surface could possibly provide the fusion fuel resource that would expedite this energy promise.

Rationale/Objectives

- An advanced fuel cycle employing *helium-3* in deuterium/helium-3 fusion reactions offers the potential of a relatively "clean" (small number of neutrons) nuclear energy source for future commercial and space exploration applications of magnetic fusion power.
- The reasonably assured reserves of helium-3 resources on Earth (about 500 kilograms) are sufficient to support demonstration plants on Earth and near-term space power applications, but are inadequate for major power generation in the 21st Century and beyond.
- Theoretical considerations and analyses of lunar rock samples indicate that as much as 1 billion kilograms of helium-3 is present within the first five meters of the lunar surface, having been deposited by the solar wind over the past 4 billion years.

Significance of Resource Utilization

- The mass of lunar helium-3 required to produce the 1985 U.S. electrical consumption (260,000 megawatt-years) is 20,000 kilograms.
- The 1 billion kilograms of lunar helium-3 could produce an electrical energy equivalent of 10 billion megawatt-years, providing an equivalent of *40,000 years of the 1985 U.S. consumption.*
- The amount of lunar surface to be mined (probably the maria, where the concentration is highest) to produce the yearly U.S. energy consumption would be about 270 square kilometers. The process energy required for mining, gas evolution, isotopic separation, cryogenic storage, and transportation to Earth is estimated to be 2,400 gigajoules/kilogram of helium-3. This yields an energy payback ratio of approximately 250, which may be compared to 20 for terrestrial uranium-235 production for light water reactors and 16 for coal mining.

Further information about this rapidly developing new area of study may be found in the upcoming September, 1986 issue of *Fusion Technology*.

wresting useful materials from lunar or asteroidal rocks is to search for new ideas and to carry out laboratory testing of both old and new ideas, with the intent of demonstrating proof-of-concept at the laboratory bench scale. In these studies, scientists who are knowledgeable about extraction processes need to communicate and cooperate with scientists who have detailed knowledge about lunar and asteroidal materials.

At this stage, experiments and tests should not be restricted to proven methods and their extensions. Bold new ideas should be sought and tested. Although there is considerable promise in several new techniques–electrostatic separation, fluoride separation, and electrolysis–we must recognize that the range of thinking has so far been very limited. The ingenuity that has historically been the American stock-in-trade has not yet been forcefully applied to the problems of using nonterrestrial resources in space.

Although the questions of economics and future major space developments lie outside the scope of this report, it is clear that studies of these questions must also be carried out as soon as possible. One group of studies should include concepts for a permanently manned lunar base that would emphasize utilization of a lunar site and would take advantage of available lunar resources. An initial design for such a base could assume a return to one of the *Apollo* landing sites to take full advantage of our current detailed knowledge of the materials there. Such studies must involve individuals with a wide range of skills–space systems engineers, technologists, economists, social planners, and space scientists familiar with the materials and conditions to be found on asteroids and the Moon.

At this moment, we do know enough to be certain that it would be a mistake to ignore the potential role of nonterrestrial resources in future space exploration and development. It would be a worse mistake to build the currently planned systems (such as the Space Station and the OTV) so that limitations in their designs make it impossible to reach, study, and eventually use such resources. We can now take a number of steps, simple and not overly expensive, to ensure that the option of using nonterrestrial resources in the future remains open to us. As we progress into space and gain new understanding about the solar system, we will at the same time uncover and assess the resources that are there to support our future space activities–not just in Earth orbit, or on the Moon, but throughout the solar system as well.

Still tethered to the mother ship, an astronaut floats across the surface of a small asteroid, prospecting for nickel-iron and other mineral samples.

CONCLUSIONS

1. The establishment of major space activities in low-Earth orbit (LEO) could create conditions in which it becomes more efficient to obtain the required large amounts of materials from the Moon or from near-Earth asteroids than to pay the major costs in fuel and facilities needed to lift them from Earth's surface. It is quite possible that, in such circumstances, the extensive front-end costs of establishing lunar or asteroidal mining and launch facilities could be repaid in the long run by the significantly cheaper transportation costs.

2. In the relatively near future, nonterrestrial materials in LEO could be used as bulk mass for radiation shielding and as a source of oxygen for propellants and life support.

3. Longer-term uses of nonterrestrial resources could develop from major construction activities in Earth orbit. For these purposes, nonterrestrial resources could be processed further to provide glasses, ceramics, and metals.

4. Nonterrestrial resources are, for the near future, to be found only on bodies that: (a) are easily accessible from Earth; (b) have small or negligible gravity fields against which materials must be lifted. The most commonly recognized possibilities are the Moon and near-Earth asteroids.

5. Despite the large amount of information about the Moon made available by the *Apollo* missions, there are still serious gaps in our knowledge about the Moon. More information must be acquired before the resource potential of the Moon can be accurately evaluated.

6. The lunar *regolith* or lunar soil, the layer of finely ground bedrock that covers the lunar surface, is the most accessible lunar material for future resources use. It has the advantages of being already crushed, easily excavated, compositionally uniform over large areas, and available in amounts more than adequate to support any anticipated human activity in space. Current data show no available water in lunar materials, but water and other volatiles might possibly be preserved in shadowed craters near the lunar poles.

7. Despite the general uniformity of the lunar regolith over large areas, certain lunar processes could possibly have concentrated certain minerals into enriched ores. Two such processes are: (a) separation of dense minerals from molten volcanic lavas under the influence of gravity; (b) vaporization and redeposition of relatively volatile elements by volcanism or impact events.

8. Available data on the chemistry and available tonnages of lunar materials indicate that they could form the basis of an extensive manufacturing technology. However, at present there is an almost complete absence of the technology needed to extract the useful materials and of the space-based economic conditions that would make their extraction profitable.

9. Asteroidal materials are also potentially available in large amounts (even from small objects). Although no asteroidal compositions are definitely known, data from meteorites and telescopic observations suggest that the materials available in asteroids are more diverse than those available from the Moon. Compositions of special interest for potential resources use are metal-rich asteroids and those similar to carbonaceous meteorites, which contain significant water and carbon.

10. The most accessible group of asteroids, and therefore the most interesting in current considerations of resources use, are the "Earth-crossers" (Apollo, Amor, and Aten groups). Energy requirements to reach these asteroids are comparable to those required to go to the Moon.

11. Asteroidal mining missions have several complications in comparison to possible lunar ones: restricted launch windows, long travel times, a need for complex spacecraft and life-support systems, and the development of mining and processing techniques adaptable to zero-gravity.

12. The greatest concern about being able to use nonterrestrial resources in the future is that virtually none of our terrestrial mining and extraction experience is applicable to space operations because: (a) terrestrial and nonterrestrial ores are fundamentally different; (b) current terrestrial mining and extraction technology is not directly applicable to the different conditions of the space environment.

13. Any future use of nonterrestrial resources will occur in the context of major human activities in space and will require the special development of an extensive infrastructure whose details are beyond the scope of this report. Available facilities in the mid-1990s will include the Space Station complex and its associated transport systems. This establishment can serve as a base for the development of additional capabilities in transportation, power, communications, and habitation that will be required to enable the use of nonterrestrial resources.

RECOMMENDATIONS

1. The lunar data base must be improved to the point where it can support definite decisions about the future use of lunar resources. In particular, the rest of the Moon's surface must be mapped at higher spatial and analytical resolution. The proposed *Lunar Geoscience Orbiter (LGO)* mission should be undertaken as soon as possible as a joint scientific and resource-assessment activity, in order to complete the global surveying of the Moon and to search for water in shadowed polar lunar craters.

2. Ground-based analytical and theoretical studies should be continued on the available lunar samples in order to generate a better resource-related data base, to identify new lunar rock types, and to estimate the possible existence of concentrated lunar ores.

Such studies should include: (a) remote sensing and compositional measurements of the lunar surface; (b) continued basic characterization of complex fragmental lunar rocks (breccias) returned by the *Apollo* program; (c) continued studies of terrestrial analogues of lunar rocks; (d) theoretical and experimental studies to determine the origins of both lunar and related terrestrial rocks.

3. Supporting studies should be expanded to help assess the nature and potential of asteroidal resources. These studies include: (a) ground-based discovery and characterization of near-Earth asteroids; (b) meteorite studies aimed at matching meteorite classes with known asteroids; (c) telescopic and radar studies of asteroids to determine their mineralogy and surface characteristics.

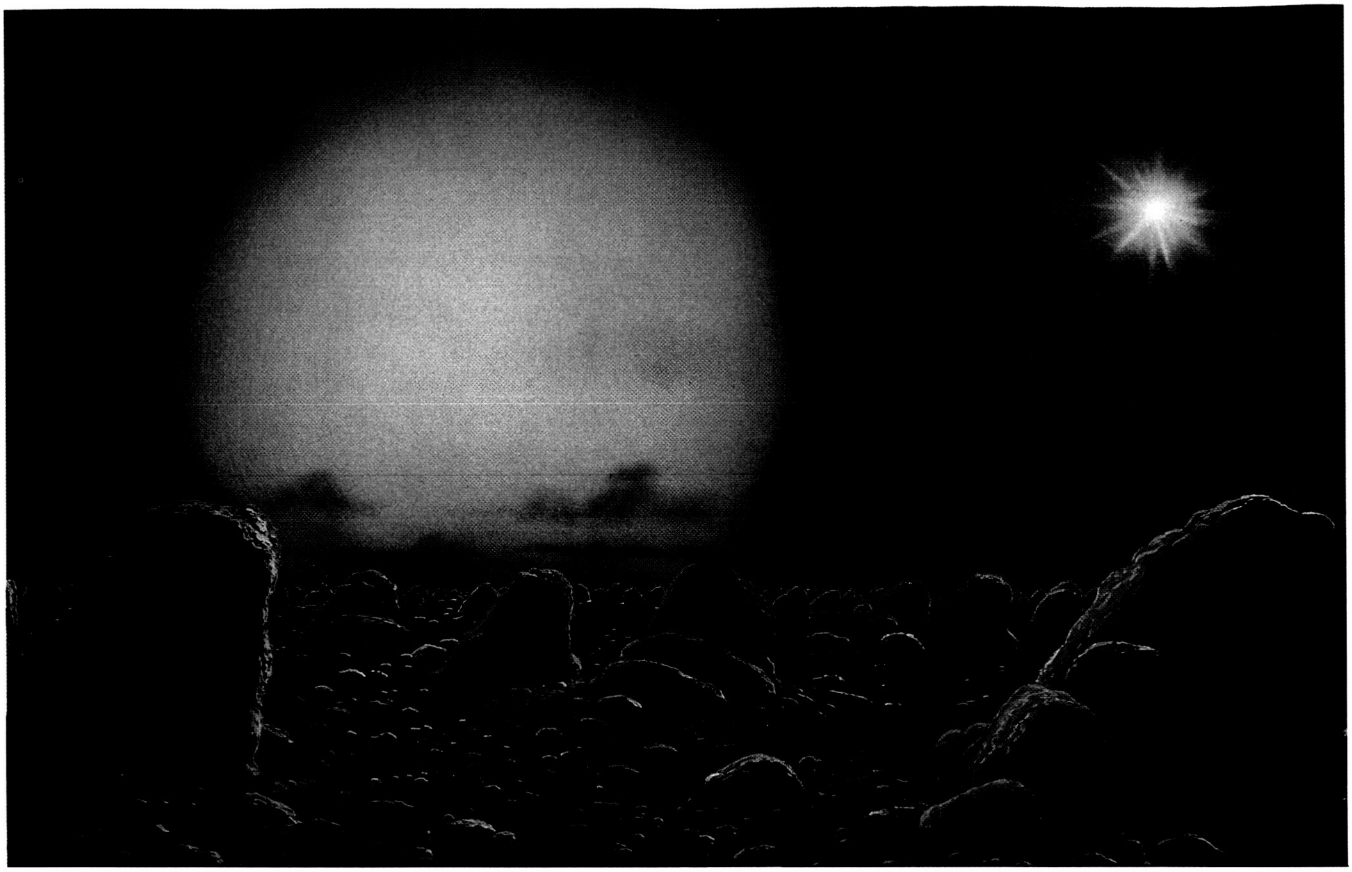
4. Detailed studies and the development of instruments for missions to characterize near-Earth asteroids in detail should be started as soon as possible. An ideal mission would combine an automated orbiter and landed probes in order to provide global mapping and geochemical sensing, surface geochemical information, and geophysical sensing to determine the depth of any surface regolith and the general coherence of the body. The *Near-Earth Asteroid Rendezvous (NEAR)* mission, already included in the Core Program, should be undertaken as soon as possible after the *Lunar Geoscience Orbiter (LGO)* to begin the close-up scientific study and resource assessment of an asteroid.

5. Theoretical and laboratory (bench-scale) tests of new extraction techniques, applicable to nonterrestrial materials and to the space environment, should be undertaken as soon as possible so that adequate technical information can become available to support serious consideration of future resource use.

6. The planning of future major space activities should be carried out in such a way as to enable, rather than foreclose, the future use of near-Earth resources. A special challenge, which must be met immediately, is to develop mechanisms for ensuring that the Space Station and its associated systems can support future resource use and that the technology developed for the Space Station is flexible enough to be applied in other environments. Provision should be made, for example, to ensure that the Orbital Transfer Vehicle (OTV) finally developed does include the modest additional capability needed to reach lunar orbit (not just GEO) from the Space Station. The development of aerocapture techniques should also be undertaken in order to make possible an efficient return trip from the Moon to LEO.

7. Design studies should be undertaken on lunar base concepts that would emphasize the utilization of lunar resources. The initial study should assume a return to one of the *Apollo* sites in order to take full advantage of our knowledge of the materials and conditions there. The studies should include representatives from *all* appropriate NASA offices to ensure that the known characteristics of nonterrestrial resources are made available early in the planning process.

Antares, a giant red star with its blue companion star, as viewed from a hypothetical planetary body.



7. Beyond the Solar System

THE SEARCH FOR NEW WORLDS

Is Our Solar System the Only One?

To understand the origin of our solar system–the Sun and its planets–has been a central goal of human thought for thousands of years, first in religion and philosophy, and later in science. Scientific research on this problem has always been hampered by the fact that only one solar system–ours–is definitely known to exist. As a result, it is impossible to understand the solar system by applying to it the traditional scientific method of comparative studies to discover the underlying laws governing its formation. To this day, studies of the origin of the solar system have shared a common attribute with theories about the origin of the universe: both are limited to a single observable example, and, so long as this is the case, theories of their origin remain, in a very fundamental way, both limited and untested.

In the case of the solar system, however, the situation is changing. Scientists are increasingly coming to believe that the solar system is not, in fact, a unique and singular object. Current theories of solar

system formation have not established any circumstances that would prevent the same process that occurred around our Sun 4½ billion years ago from occurring around other stars. Furthermore, an increasing number of limited, but highly suggestive, observations supports the idea that planetary systems do occur around other stars and may in fact be common:

- The presence of small, invisible companions of stars, possibly of substellar mass, is suggested by long-term astrometric tracking of stars in the solar neighborhood.
- Measurements from the *Infrared Astronomical Satellite (IRAS)* and other infrared observations have detected disks made up of solid particles (but no planet-sized bodies) around several nearby stars. These same disks have also been recently detected by ground-based observations.
- A companion of the star Van Biesbroeck 8 has been detected by ground-based infrared observations. This object, called a "brown dwarf," has many times the mass of Jupiter and a surface temperature of about 1,100° C., conditions which do not fit our traditional picture of a planet, but it also lacks the energy-producing nuclear reactions that characterize actual stars. There may be many more of these nonstellar objects circling other stars.

Looking at the state of current theories and observations, most scientists concerned with the origin of the solar system would be quite surprised if similar planetary systems turned out *not* to be common in the universe. But the history of science is littered with the debris of similar comfortable assumptions that were shattered by new observations. It is essential that we search for other planetary systems in order to test our ideas and to find out what the universe is really like.

By discovering other planetary systems, we could directly determine the general characteristics of such systems and reach a deeper understanding about their origin–and ours. The knowledge that other planetary systems are common would also provide a firmer basis for one of the stepping-stones in the current arguments we make about the probability of life elsewhere in the universe. If life is limited to planets, and if planets are common, then the chances for extraterrestrial life are greater than if planets are rare. By the same token, the discovery that planetary systems are rare would force us to make major changes, not only in our theories about the formation of stars and the origin of the solar system, but also in our thoughts about the place of humanity in the universe.

The present time has become especially ripe for considering such planetary detection projects in detail. Advancing scientific technology, combined with the developing capability to carry large instruments into orbit above Earth's atmosphere and to support them for long periods of time, will soon make it possible to detect and study planetary systems similar to ours around a large number of nearby stars.

Such an endeavor would have major scientific and human impacts, whatever the results. In addition, the undertaking is a

logical part of the NASA mandate, for it involves several major areas of current space science–the nature of the solar system, the mechanisms of star formation, and the possible existence of life elsewhere in the universe. The search for other planetary systems is also especially suited for inclusion in the Solar System Exploration Division because it addresses one of its fundamental program goals: to understand the origin and evolution of our solar system.

For these reasons, a general discussion of the current state of, and the future prospects for, the detection and study of other planetary systems is included in this report. In this chapter, we discuss the scientific basis for such a search, its potential impact on understanding the origin of our own solar system, the status of current development activities and plans, and some recommendations for the future.

The Nature of Planetary Systems

STRUCTURE OF OUR SOLAR SYSTEM

Centuries of study have established the fact that our own solar system displays several fundamental regularities in its structure. These features, many of them detected hundreds of years ago, indicate that the mechanisms that formed the solar system were not chaotic and random. Instead, the formation of the solar system seems to reflect the operation of well-behaved (if not yet well-understood) physical processes, operating in a single object–the protosolar nebula–to form the Sun and the planets.

Most of our current clues to the origin of the solar system have been provided by observations of the Sun and its family–planets, asteroids, meteorites, and comets. The planets are not randomly distributed around the Sun; their orbits are approximately circular and concentric. The planets all move in the same direction around the Sun, and they move nearly in the same plane. Furthermore, this common plane of planetary motions is roughly in the equatorial plane of the Sun's rotation. In general, the planets' axes of rotation are nearly perpendicular to the plane in which they rotate around the Sun. (Uranus, whose axis is almost parallel to the plane, is an interesting exception.) There is also an approximately geometrical regularity in the distances of the planets from the Sun, expressed by the so-called Titius-Bode Law.

In addition, both the masses and compositions of the individual planets are arranged in an orderly fashion. In the inner solar system, close to the Sun, the so-called terrestrial planets (Mercury, Venus, Earth, and Mars) are comparatively low in total mass, and they are composed primarily of silicate rocks and metal, refractory substances that will condense out of a heated mixture of solar-composition material at high temperatures (in excess of 1,000° C.). By contrast, in the outer solar system, far from the Sun, the so-called Jovian planets (Jupiter, Saturn, Uranus, and Neptune) are much more massive and are composed largely of gases (chiefly hydrogen and helium) and ices. Some of these relatively volatile substances (such as water, methane, ammonia, and nitrogen) can condense to solids only at low temperatures, less than a few hundred degrees

Kelvin; other species (such as hydrogen and helium) remain gaseous under nearly all natural conditions.

Crudely, then, it seems that the masses of the planets vary in proportion to the cosmic abundance of the atoms which dominate their composition: the massive Jovian worlds are composed of abundant hydrogen and helium, while the less massive terrestrial planets are made up chiefly of the rarer refractory elements–iron, silicon, nickel, aluminum, calcium, and others.

ORIGIN OF OUR SOLAR SYSTEM

Present theories about the origin of our solar system are all based on one generally accepted concept–that the Sun and the planets formed, nearly simultaneously, about 4½ billion years ago, out of a single object–the protosolar nebula.

The following discussion briefly describes our current understanding of how the basic structural regularities of our solar system arose as the natural result of the ordinary evolutionary processes involving the birth of a single star.

Astronomical observations of other stars indicate that they are forming from preexisting clouds of interstellar dust and gas, which collapse under the influence of their own self-gravity. At first, these clouds are extended and diffuse objects, perhaps 100 times larger than our present solar system. Because of the general rotation of the Galaxy, as well as the independent random motions of each cloud, these interstellar clouds rotate slowly around an internal center.

The change from such a slowly rotating cloud, to a collapse phase, and finally to the formation of a star and an associated planetary system, is estimated to take only from a few thousand to a few million years. Surprisingly, these theoretical estimates have been supported by recent work on meteorites, in which extinct radioactive isotopes have provided estimates of the time between the formation of radioactive elements in the cloud and the production of solid objects; this time is less than a few million years for our own solar system.

If we could follow the collapse of a typical interstellar cloud, we would see matter gradually flow inward toward the center under the influence of the cloud's self-gravity. As this happens, the original rotation of the cloud speeds up as the size of the cloud decreases, because of the tendency for the original angular momentum of the cloud to be carried with the collapsing gas. (A common example of this process is an ice skater, who spins slowly with the arms extended and then speeds up when the arms are drawn in toward the body.) The centrifugal force inhibits the cloud's collapse *toward* the axis of rotation, but allows the collapse *along* the rotation axis to proceed freely. As a result, the original irregular cloud assumes the shape of a flattened disk–called the protosolar nebula–rotating around an axis perpendicular to the plane of the disk.

The typical structure of such a disk has most of the mass concentrated in the center of the disk rather than at the edges, and the center therefore rotates more rapidly. As the disk evolves, however, frictional effects between the more rapidly moving gas and dust particles in the center of the disk and the slower matter further

out tend to slow the rotation in this area and to decrease the angular momentum in the central part of the disk. To keep the total angular momentum constant, the angular momentum of the material in the periphery must then increase; some of the material therefore moves outward, leaving the remaining material to accumulate at the center and to form a star.

Energy is rapidly deposited in the central part of the disk by the frictional, dissipative effects in the gas and dust; the ultimate source of this energy is gravitational energy carried by material that falls inward to the center from the periphery. This energy serves to heat the central part of the disk. At the center, where most of the mass is concentrated, temperatures will eventually reach a few million degrees Centigrade, high enough to initiate the thermonuclear reactions that characterize a star. At moderate distances from the center, the gas pressures and mass concentrations are much lower, but temperatures can still rise above 1,200° C., or above the melting point for most natural compounds. Much farther out, temperatures will be much lower–less than a few hundred degrees Kelvin.

The development of this radial temperature gradient inside the protosolar nebula has a major effect on the materials out of which the planets will form. At any point in the nebula, some of the material will be solid and some gaseous, but the relative amount of solid material, as well as its chemical composition, will vary with the temperature and thus with the position in the nebula. In the inner part of the nebula, at less than one Astronomical Unit (AU) from the center (i.e., inside the present orbit of Earth), only the more refractory chemical compounds–such as oxides and silicates of calcium, aluminum, titanium, magnesium, and a few other elements–can condense to form dust particles. With increasing distance from the center, the temperature falls, and a progressively larger fraction of the nebular material becomes stable in the solid state. Beyond a few Astronomical Units from the center (i.e., beyond the present asteroid belt), temperatures are low enough for even the relatively abundant volatile components–chiefly water–to condense and form solid particles. (The *Astronomical Unit* or AU, which is the distance between Earth and the Sun–150 million kilometers–is a convenient yardstick for discussing locations in the solar system.)

An idealized steady-state nebula will consist of a mixture of gas (chiefly hydrogen and helium) and solid particles (dust and ice), and both the amount of solid particles and the amount of ice relative to dust will increase outward. The observed compositions of the planets in our solar system suggest that planet formation was dominated by accretion of the solid particles. In this view, the inner four terrestrial planets formed directly through a process of accretion beginning with silicate and metal dust particles in a region where ice particles were largely absent. The total mass of original dust involved in the accretion of the terrestrial planets is not known, but it is possible that the accretion process was very efficient and captured a large fraction of the available material.

In the outer solar system, the more abundant volatile materials condensed to ices, and the resulting solids apparently accreted to form massive ice-rich planetary cores. For two of these objects–

which became Jupiter and Saturn–the gravity of the massive cores apparently produced a subsequent hydrodynamic collapse of a gaseous envelope from the surrounding nebula. In this way, a large quantity of original nebular gases was trapped around the original ice cores to form the massive atmospheres now observed on these two planets. For reasons that we still do not understand, the gaseous envelopes captured by the other two ice-rich cores–those of Uranus and Neptune–were not nearly as massive. A more accurate and complete picture might show that the formation of the planetary ice cores and the hydrodynamic gaseous collapse occurred simultaneously and interactively, but the relation between these two processes still remains one of the many unexplained aspects of our theories of planet formation.

The origin of our solar system's regular composition and structure can now briefly be summarized. An original interstellar dust cloud collapsed into a centrally condensed, flattened disk–the protosolar nebula–as the result of the interplay between several complex forces: self-gravity, angular momentum, and highly dissipative frictional mechanisms in the dense central regions of the disk. These processes produced the overall geometric and rotational structure of our solar system. The matter in the disk separated into solid and gaseous components, and the relative amounts of each were controlled by local temperature (and hence by position) in the disk. Planet formation, involving accretion of the solid particles, produced a group of objects whose masses and chemical compositions show regular variations with distance from the Sun. The variations produced by these processes match those observed in our own solar system.

STAR FORMATION AND OTHER PLANETARY SYSTEMS

Our present understanding of the formation of stars and planetary systems has been built on a variety of studies of our own solar system and from telescopic observation of star-forming interstellar cloud complexes elsewhere in the universe. In our own solar system, critical information has been obtained from both remote and on-site observations of other planets and planetesimals, as well as from the analysis of available samples of extraterrestrial materials. Although many unanswered questions still remain, we have a fair degree of confidence that our overall picture is basically correct.

Our current theories imply that the origin of the Sun and the solar system was not a unique, or even a remarkable, event. The conditions and mechanisms for the Sun's formation are similar to those associated with the formation of many other stars that we can now observe, and they are also similar to the behavior of stars that we can observe in the process of formation at this time.

Observations of protostellar systems, which are now becoming extensive and detailed, confirm that the conditions inferred for the birth of our solar system were not unusual and are, in fact, being duplicated in the universe at the present time. Both indirect and direct observations, for example, are confirming the critical role of rotation and angular momentum redistribution during the formation of stars. Disks of solid material, similar to the disk

Recent Discoveries of "Planets"

At first glance, the detection of planets around other stars from Earth-based observations seems totally impossible. At a distance of a few light-years, the planet, illuminated only by its parent star, is a dim speck virtually lost in the glare from the star. Nevertheless, in the last few years, Earth-based astronomers have ingeniously devised methods for detecting distant planets. However, because the observable effects of planets lie at or below the level of disturbance induced by Earth's atmosphere for most observation techniques, there are, as yet, no reliable indications of other planetary systems.

One type of investigation *(astrometry)*, which has been used for decades, involves careful measurements of the star's position in the sky. If the star is accompanied by a large enough planet, the pull of the planet's gravity will cause the star to wobble slightly back and forth in the sky as the planet moves around it from one side to the other. Careful measurements, carried out over long periods of time, can detect such wobbles in at least the nearest stars.

Another method for detecting planets is *infrared astronomy*, in which a special kind of telescope is used to detect, not the visible light radiated by hot stars, but the infrared (heat) radiation produced by cooler solid material. Infrared telescopes can view directly some substellar objects that may be orbiting stars, if the objects are large enough or numerous enough.

The *Infrared Astronomical Satellite (IRAS)* recently detected disks made up of fine solid particles orbiting several nearby stars: Vega, Fomalhaut, and Beta Pictoris. The observtions could not detect whether any actual planets were present.

Ground-based infrared observations recently detected another non-stellar object, a large companion, invisible to normal telescopes, orbiting around the star Van Biesbroeck 8. It is clearly not a planet of the kind we are used to; it is much heavier and denser than Jupiter and hot enough at its surface (1,200° C.) to glow redly, like an ember or a freshly erupted lava flow. Objects like these–too big to be familiar planets and too small to produce the nuclear reactions that would make them stars–have been named "brown dwarfs." Astronomers are now searching for more of them, and many suspect that, if there are a lot of them orbiting other stars, there may be more conventional planets as well.

How to Look for Other Solar Systems

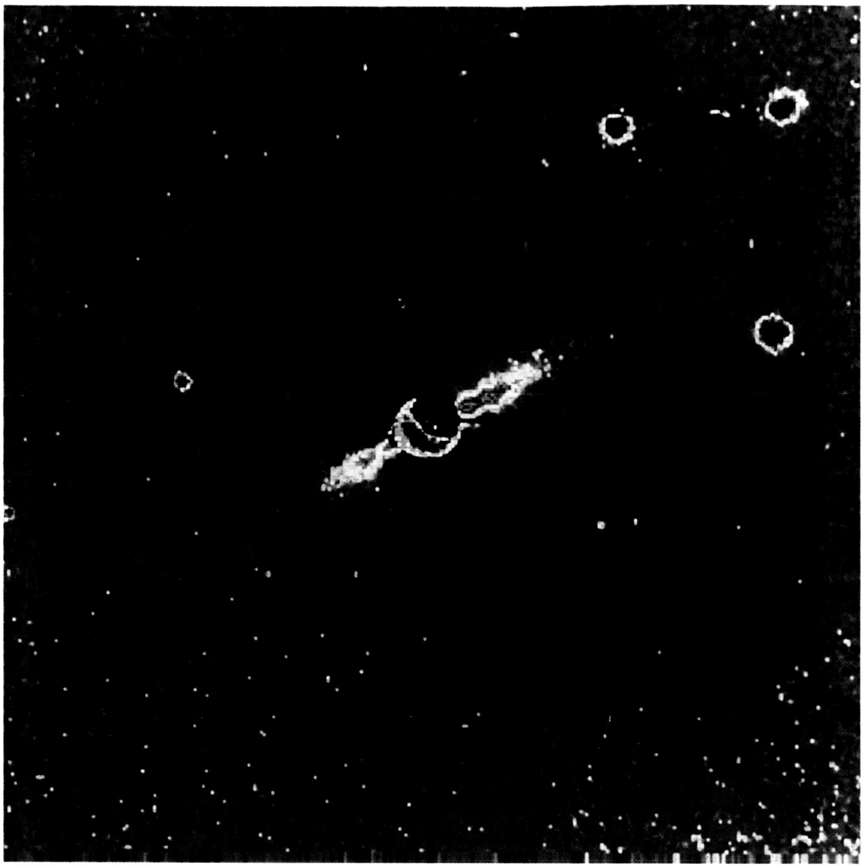
The search for planets around other stars is already being carried out with a number of ground-based techniques. New methods, applied both on the ground and in space, hold even more promise for the future. Brief summaries of the major techniques that scientists are now using, and hope to use in the future, are given below:

Indirect Methods: These techniques attempt to detect the planet by observing its influence on the parent star.

- *Astrometry.* In this method, precise, long-term measurements of a star's position are used to detect slight back-and-forth "wobbles" produced by the gravity of unseen planets moving around it. Measurements from the ground have already indicated such wobbles in the positions of at least two nearby stars, Barnard's Star and Van Biesbroeck 8. An astrometric telescope in space, now being studied as an addition to the planned Space Station, will be capable of far more accurate and decisive measurements that will tell us whether planetary systems are common or whether they occur only rarely in the universe, and will also be able to determine the properties of other planetary systems.
- *Radial-velocity measurements.* This technique also detects motions of a star produced by unseen companions. In this case, the velocity of the star is determined relative to Earth by measuring the Doppler shift in the star's spectral lines. Long-term measurements can detect periodic changes in the star's velocity produced by the gravitational pull of its planets. A program of very highly accurate ground-based measurements has recently been started.
- *Luminosity measurements.* If an unseen planet passes in front of a star, it blocks out part of the star's light. By measuring the luminosity of the star for long periods of time, periodic variations in brightness caused by the passage of planets in front of the star can be detected.

Direct Methods: The purpose of these methods is to detect radiation coming directly from the planet. Current techniques detect two types of radiation: visible starlight reflected from the planet, and infrared radiation produced by internal heat in the planet itself and by the thermalized starlight. Ideally, these radiations can be used to form an image of the planet and perhaps even to measure its composition, just as is done with planets in our own solar system.

- *Optical astronomy.* Direct imaging of planets around other stars, while difficult, might be done by a new generation of telescopes in space. Future telescopes, using special techniques to reduce glare and scattered light from the primary star, might be able to detect planets by observing from space.
- *Infrared astronomy.* Infrared telescopes, both on the ground and in space, have recently detected solid objects around stars. The orbiting *Infrared Astronomical Satellite (IRAS)* detected disks of small particles around several stars, and a ground-based infrared telescope recently detected a large "brown dwarf" object around the star Van Biesbroeck 8. Ambitious infrared telescopes planned for the future will make important contributions to investigations of substellar objects and of star and planet systems in the process of formation.
- *Interferometry.* This technique can be applied to improve the sensitivity of both optical and infrared telescopes. It involves careful comparison and analysis of images of the same object obtained from two or more separate telescopes. Used with ground-based infrared telescopes, interferometric techniques helped discover dusty disks around other stars and the "brown dwarf" companion of Van Biesbroeck 8. Established in space, arrays of interferometric telescopes will be far more sensitive and precise.



This false-color image of Beta Pictoris shows a circumstellar disk of material extending 60 billion kilometers from the star.

thought to form our own solar system, have now been observed around other stars and seem to occur commonly as the wombs of star birth.

From these studies, it has now become reasonable to suppose that many stars have planetary systems. Moreover, since the gross structural features of our own solar system seem to have emerged, not by accident, but as a general consequence of the nearly inevitable physical characteristics of the protosolar nebula, it is also reasonable to expect that the overall structure of our solar system–as summarized earlier–is a fair representation of other planetary systems we might find.

Nevertheless, we must always remember that this reasoning is somewhat circular. Our cosmogony and our ideas of general mechanisms have been selected and adjusted to explain only the one solar system available for close study–ours–and we have no way of knowing whether our ideas are as general as we think they are. This situation will not change until we can obtain some objective information about the abundance of planetary systems in the universe and about the similarities and differences among them.

The Search for Other Planetary Systems: Why Now?

From the purely scientific point of view, we have now come to the point at which efforts to discover and study other planetary systems

are not only timely–they are in many ways essential for further progress. The abundance of planetary systems in the universe is a fundamental piece of objective data which we must have in order to construct, test, and modify our theories. The discovery of other planetary systems, and the study of them at a level sufficient to reveal structural regularities like those which characterize our own system, have now become essential if we are to turn our theories about star and planet formation into a real and objectively based science.

From the technical point of view, the capabilities needed to search for other planetary systems are also coming within our reach. One of the major barriers to such searches is Earth's atmosphere. Scattering and distortion of light by the atmosphere is a large impediment to astronomical observations of the quality needed to detect and examine other planetary systems. The only solution is to carry our instruments above the atmosphere–into space–a long-standing astronomical dream that is only now beginning to be realized.

In addition to freedom from the atmosphere, detailed searches for other planetary systems have a second essential need–time. Such searches must extend at least over a period of time comparable to the revolution of the major (and most detectable) planets around the central star. (For our own solar system, this would require observations over 12 to 30 years for Jupiter and Saturn.) Such long-term observations are essential to provide the orbital information upon which accurate measurements of the planetary masses can be based. Therefore, the initial search must be established with the capability to be continued for at least a decade, with the option to extend the search for a considerable period beyond if the results of the early observations warrant it.

The permanent Earth-orbital infrastructure that will become available with the establishment of the Space Station is especially well-suited to meeting both of these requirements. A permanent Space Station, including the infrastructure adequate to support operation of high-quality astronomical instrumentation over long periods of time, will, within a decade, make serious and significant searches for other planetary systems possible.

An extensive search for other planetary systems, whatever the outcome, cannot help but have a major impact. If other planetary systems are found, then new directions will open up in both science and philosophy. Our own planetary system will become firmly established as only one specific instance of a general phenomenon.

On the other hand, if no other planetary systems are found after an exhaustive search, we will have to admit that planetary systems like ours are uncommon, and perhaps unique, in the universe. Our ideas about the formation of our solar system will have to be reexamined in the light of evidence that the system is a cosmic accident, some freak of nature, and not representative of anything general.

Whatever the outcome of such a search, the results will be electrifying, both from a scientific perspective and from a broader human perspective. The results will penetrate to the core of our perceptions about our place in the universe.

Planets in nebulosity near an orange star.

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COLOR PHOTOGRAPH

SCIENTIFIC OBJECTIVES FOR THE SEARCH

Using our solar system as a model, we can speculate that the principal components of another planetary system are: the central star, an assemblage of planets (perhaps about ten), and a large number of minor bodies: asteroids, comets, and smaller objects down to microscopic particles of cosmic dust. Of all these objects, only the central star can be easily detected. To discover any of the other components in the system, careful and persistent measurements must be made. This section reviews some of the general techniques that might be employed.

Regardless of the particular methods used, the study of other planetary systems should be carried out so that the principal structural regularities of the other systems can be objectively determined and compared directly with our own. As discussed above, such objective features as the orbits of the planets and the distribution of planetary compositions and masses with distance from the central star have provided an essential foundation for our theories about how planetary systems form. In designing our observations, however, we should not be too influenced by what we have observed in our own solar system. Although we have considerable confidence in our theories, we must remember that they are just theories–and other planetary systems may turn out to be considerably different from our own.

The specific scientific objectives of a search for other planetary systems are influenced by at least three major considerations:

- The information obtained should be of sufficient quality and quantity to critically address the major questions in this area.
- The investigation must be intense and thorough enough to make the result credible, regardless of whether the result is positive or negative.
- The investigation should be general enough so that it can detect and examine planetary systems whose properties turn out to be significantly different from what we expect on the basis of our own solar system.

Some of the scientific constraints that result from these considerations are:

1. ***A moderately large number of stars must be investigated in order to ensure that the results are as general as possible.*** A large fraction of these targets should be single stars, because (again according to our theories), the existence and stability of planets in multiple star systems is uncertain and problematical. The ability to investigate approximately 100 single stars requires that the search extend to about ten parsecs from the Sun. (The *parsec,* which equals a distance of 3.26 light-years or 3.1×10^{13} kilometers, is a standard unit for measuring interstellar distances.)

2. ***The measurement techniques should be capable of detecting and measuring the orbits of planets with masses as low as those of Uranus and Neptune.*** By detecting these largest planets, the locations of the dominant planet-forming chemical species in the system can be

defined and compared with what we have deduced from our own solar system. For example, such an examination of our own solar system from the outside would establish the existence and orbits of the volatile-rich, massive Jovian planets and would, by inference, suggest the existence of smaller, less massive terrestrial planets closer to the Sun.

The discovery of such large planets in orbits comparable to those of Jupiter and Saturn around another star would then justify major efforts to develop techniques to detect terrestrial-type planets closer to the star. On the other hand, the absence of any planets of the mass of Uranus and Neptune or larger, from a significant sample of local stars, would put our present ideas about planetary formation into serious jeopardy.

3. The observing program must extend for at least one to two decades. The dominant condensible planetary components in a mix of solar or cosmic composition will form relatively volatile ices that are stable only at relatively low temperatures. For this reason, we expect that the largest planets in a planetary system will be found farther than a few Astronomical Units from the central star, as is the case in our solar system. Planets at these distances can be expected to have orbital periods on the order of decades.

Measurements must be continued over at least the major part of an orbital period, in order to provide the accurate orbital measurements needed to determine the exact masses of the planets.

TECHNICAL APPROACHES TO PLANETARY DETECTION

There are several possible methods to detect and characterize other planetary systems. This section briefly describes the few approaches that seem to be most promising at present. It is essential that all of these techniques, and others if they can be identified, be evaluated in detail as to their suitability.

Technical approaches to the detection of other planetary systems can be divided into two types: direct and indirect. Direct methods seek to detect radiation from the planetary body itself and to form some kind of image of the object. Indirect methods seek to detect the planet by measuring its influence on the central star. Each class of methods has advantages and disadvantages, and the two methods do in fact provide complementary information.

Direct methods for detection of planets around other stars imply the use of imaging methods, either direct (immediate) imaging or the use of interferometric techniques. In both cases, the greatest difficulties to be overcome result from the very large brightness contrast between the planet and its star, combined with the relatively small angular separation between them. For direct imaging of extrasolar planets, the "washout" due to scattered light from the star is a fundamental problem.

Indirect techniques for planetary detection involve very accurate measurement of the small changes in a star's position, velocity, or luminosity caused by surrounding planets. Small shifts in the star's position occur because the orbital movement of the planet actually consists of the movement of *both* planet and star around a common

C-3

center of mass. If the planet is massive enough, the star will actually move back and forth by a measurable amount as the planet orbits it. (In a system with more than one large planet, the principle is similar but the actual interpretations are more complicated.)

The resulting movements of the star can be measured. Variations in position can be detected by highly precise astronomical measurements *(astrometry)*. Variations in the star's motion, projected along the line of sight to Earth (the so-called *radial velocity*) can be measured by the Doppler shift of the star's spectral lines. These two approaches, which measure deviations in the motion of the central star, are together referred to as *dynamical measurements*.

A different indirect method involves careful measurement of the intensity of light *(luminosity)* from a star, in the hope of detecting changes caused when the star is partially occulted by an unseen planet passing in front of it. (A similar technique has long been used to study a group of binary stars called *eclipsing binaries*.) This technique could be applied simultaneously and continuously to monitor a large number of stars, and it could make an important contribution to determining statistically the number of existing planetary systems. However, this technique does not now seem adequate to provide the detailed information–masses and orbital characteristics of both large and small planets–needed to answer major scientific questions about other planetary systems.

It should be emphasized that the direct and indirect techniques for planetary detection–imaging and dynamical methods–are complementary rather than overlapping. Each technique provides unique and important information about the properties of the planetary system. In principle, imaging techniques, once developed, can provide direct data on the sizes and physical properties of planets, including the potential to make possible spectroscopic measurements to determine planetary compositions directly.

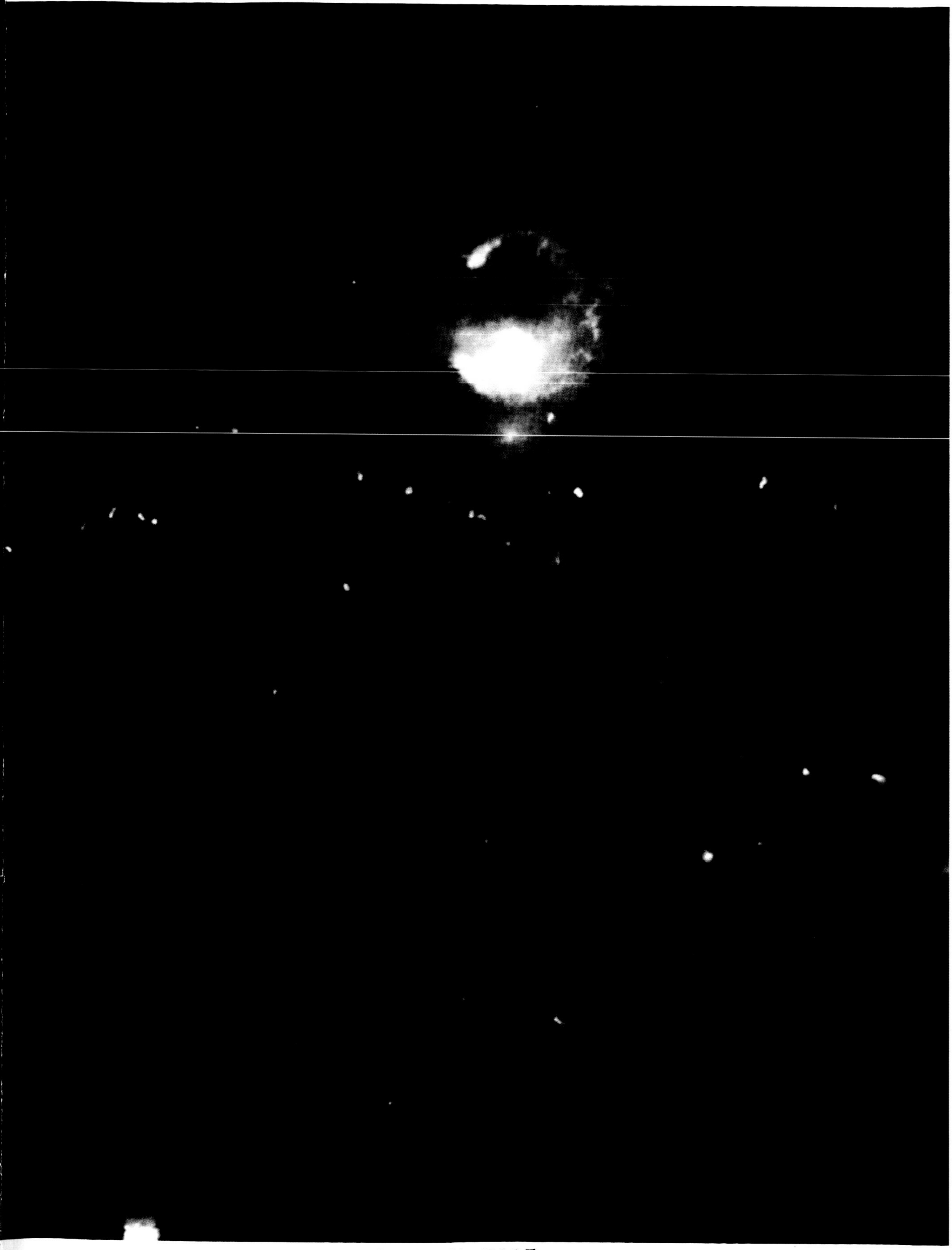
In contrast, dynamical measurements are essential to determine the structural characteristics of planetary systems, especially the orbital elements of the planets and the distribution of planetary masses with distance from the central star. These data are perhaps the most diagnostic information that we can obtain remotely to advance our understanding of other planetary systems and their formation.

Space-Based Techniques

During the past decade, the Solar System Exploration Division has supported several workshops and contractor studies to examine the feasibility of various approaches to detecting and studying other planetary systems. Some of the conclusions from these studies are summarized here to indicate the current discussion of this research area. However, none of these studies was intended to be exhaustive, and they all predated the national commitment to establish a permanent Space Station in the 1990s. More thorough studies, which take into account the potential capabilities provided by the Space Station, are essential to define better the range of possible investigations.

A portion of the Milky Way as viewed by the Infrared Astronomical Satellite (IRAS) *shows regions of gas and dust out of which massive new stars, thousands of times brighter than the Sun, are forming. The coldest regions are red and the warmer regions are blue. The yellow-white areas are bright in*

the IRAS bands, but not apparent in visual photographs, because the newly formed stars are still embedded in placental gas and dust clouds that are optically opaque. The visible light energy emitted by the stars is absorbed by the clouds, heating them and making bright infrared sources.



USE OF THE SPACE STATION

One uniform conclusion of these studies is that Earth's atmosphere constitutes a virtually insuperable barrier to any intensive program to discover and study other planetary systems. Observations from space are essential to achieve the scientific objectives. Moreover, observations from space *can* achieve these objectives.

The establishment of a permanent Space Station in Earth orbit, and the technical support infrastructure associated with it, will make possible the long-term, atmosphere-free observations essential to detect other planetary systems and to study them in detail. For several reasons, the Space Station structure itself (in contrast to a free-flying spacecraft associated with the Space Station), provides some potentially substantial advantages for undertaking such a program.

ASTROMETRIC MEASUREMENTS

To determine the detailed structure and dynamics of other planetary systems requires the full range of information that only astrometric measurements can provide. At present, it seems that the most feasible and best-suited technical approach for the foreseeable future is a space-based astrometric telescope which can measure stellar positions to an accuracy of approximately 10^{-5} seconds of arc. In reaching this conclusion, the studies examined a variety of proposed methods, taking into account the current state of the art in terms of demonstrated scientific technique, the existence of working ground-based instruments, and foreseeable advances in technology and instrumentation.

Astrometric measurement techniques have developed through a long history of ground-based observations. Recently, an electronic multiple-aperture photometric astrometric telescope has been developed and put into operation at the Allegheny Observatory, and it is now carrying out an active program of ground-based measurements. The measurement accuracy is a few milli-arcseconds during a fraction of a night of observing; this accuracy is limited only by atmospheric "seeing." The studies concluded that the same technique can readily be adapted to an Earth-orbital environment. By removing the atmosphere-generated constraints, and by using care in the construction of the instrument, a similar instrument in space can achieve the scientific objectives cited here.

Astrometric measurements can also be based on an interferometric approach as well as on direct imaging. The interferometric technique is straightforward in principle, and efforts have been devoted to developing this approach and to demonstrating its feasibility. So far, no working prototype instrument, which might be adapted to a ground-based or space-based observing program, has yet been developed. However, in the more distant future, interferometric astronomy could provide an order-of-magnitude improvement in measurement accuracy, a development which could lower the detection sensitivity to the level of terrestrial-mass planets.

At present, a definition and development effort is going forward, based on the concept of an astrometric telescope which uses an

electronic multiple-aperture photometric device and which is attached to the Space Station. This effort is being carried out under a joint agreement between the NASA Ames Research Center and the University of Arizona, in collaboration with the Allegheny Observatory of the University of Pittsburgh. The goal of this effort is to design such a telescope, devoted primarily to the detection of other planetary systems, which could then be installed as part of the Initial Orbital Capability (IOC) of the Space Station. In addition to its importance for planetary detection, the astrometric data from such a telescope would have important astrophysical applications.

IMAGING TECHNIQUES

Successful imaging of extrasolar planets requires the development of extraordinary techniques for dealing with the combination of great luminosity difference and close proximity between a planet and its star. Even above Earth's atmosphere, scattered light is a major problem in an imaging telescope. However, effective measures can be taken, both in telescope design and in data processing, to overcome this problem.

Low-scattered-light telescope technology is an area of great potential promise for the future study of planetary systems, both ours and others that may be discovered. In addition to the exciting possibility of imaging planets around other stars (and the host of scientific possibilities generated thereby), low-scattered-light imaging has important potential in studying the diffuse matter around other stars. For example, the recent discovery of a dust disk around the star Beta Pictoris is an important contribution to our thinking about circumstellar solid matter and its significance for the formation of planetary systems.

Current and Future Ground-Based Studies

Ground-based research is currently emphasizing several techniques that can be used beneath Earth's atmosphere to detect and study other planetary systems. This work is laying the foundation for what will become the next generation of space-based instruments and observations. However, independent of the possible applications in space, there is a considerable potential for making important scientific advances from the ground.

RADIAL-VELOCITY MEASUREMENTS

Radial-velocity measurements are especially suitable for the rapid detection of high-mass objects in orbits close to their central stars. Such measurements, based on analysis of the spectrum of the star at different times, are unimpeded by the atmosphere. However, the measurement technique requires spectroscopic Doppler-shift measurements with an unprecedented accuracy and long-term stability. After about a decade of intensive development, a program to make such measurements is now in its early stages.

This program will provide two important contributions to our understanding of planetary systems. First, the program will probe the existence of large-mass planets close to their central stars. The

Allegheny Observatory: The Search for Other Planets Goes On

While scientists plan to take new instruments into space to search for extrasolar planetary systems, one of the longest continuous searches is still going on here on Earth. The Allegheny Observatory of the University of Pittsburgh, located in Riverview Park on the north side of the city, is still using one of the best-known astrometric telescopes of the 20th Century to plot the movements of binary stars and to search for unseen planetary companions. The search was initiated in 1976, using a photographic technique that can observe from nine to ten stars within 15 light-years of Earth. Later, a more sensitive photoelectric technique was incorporated, increasing the detection capability of the system to up to 30 stars. To date, no planets have been discovered.

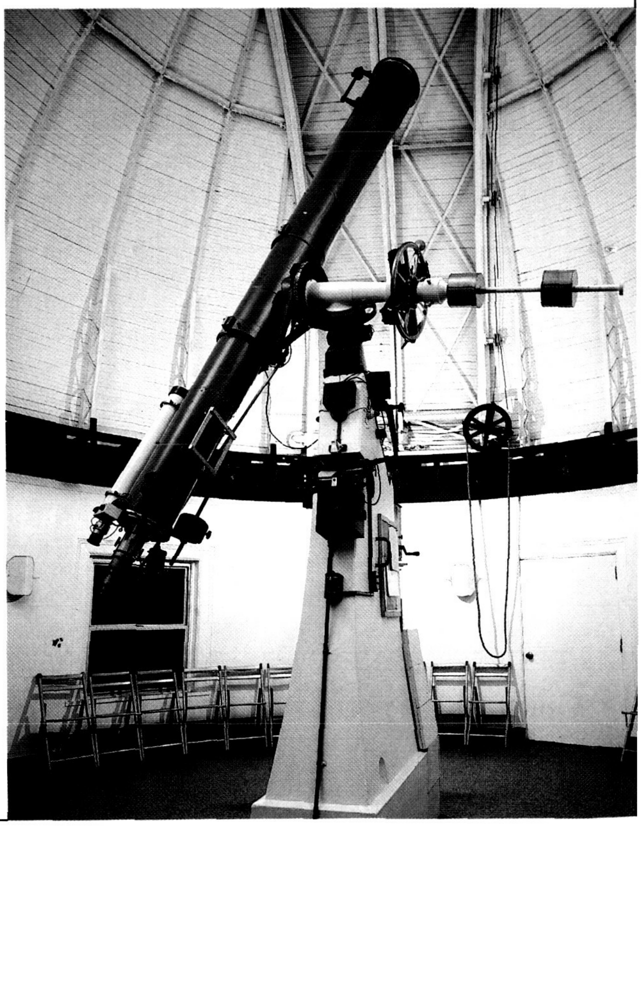
The Allegheny Observatory was established in 1912, largely by contributions from local patrons, and the Observatory building now contains three telescopes. The search for other planets is being carried out with the largest of the three, the 76-centimeter Thaw refractor, named after two of the donors, which was completed in 1914. The telescope's focal length is 14.2 meters, and the original compound lens, designed specifically to focus blue light, was made by the company of John Brashear, one of the Observatory's founders and one of the most famous telescope makers of the time.

The Observatory's search for other planetary systems uses the technique of astrometry, precise measurements of a star's position to detect movements caused by the gravitational pull of planets orbiting around it. Beginning in 1912 with the pioneering work of the Observatory's first director, Frank Schlesinger, almost 112,000 photographic plates have been taken and used to measure the locations and movements of 2,100 stars and the orbits and masses of many binary stars.

The high quality of the telescope has produced measurements of unsurpassed quality over the past 72 years. Fortunately, for these types of measurements, a steady atmosphere is more important than a totally dark sky, and the Observatory has been able to continue its program with little difficulty despite the growth of Pittsburgh and the accompanying glare in the sky.

The 72-year-old telescope has recently undergone some space-age modifications to improve its search. In 1985, with the aid of private contributions, the original Brashear lens was replaced with one designed to focus red light instead, a change that both reduced the effects of sky brightness and increased the precision of the measurements. Earlier, a new electronic detector, the Multichannel Astrometric Photometer (MAP), had been added, which improves the accuracy of the telescope by an order of magnitude. This upgrading is making it possible for the telescope to expand its studies of the positions and orbits of stars to making an extensive search for their possible companions.

Thaw measurement refractor at Allegheny Observatory.



discovery of such large planets, relatively closer to the star than is the case in our own solar system, would establish the existence of planetary systems different–perhaps fundamentally so–from our own. Secondly, the program will examine binary stars characterized by low mass and small separations. This study is likely to be an important probe into the processes of star formation; in addition, the question of whether multiple stars can (or do) have planetary systems is a central issue in this area of science.

ASTROMETRY

The ground-based astrometric methods described earlier, if limited to foreseeable technological developments, cannot achieve the measurement accuracy required for rigorous detection and study of planetary systems. It is possible that, with advances in technique and system design, it might become possible to make measurements with an accuracy of a few tenths of a milli-arcsecond, and there might be planetary systems that could be detected at that level of measurement. Such a ground-based facility would be highly desirable for a number of diverse research projects, but results at that level of accuracy would not provide the required strong test of our ideas about the formation and abundance of planetary systems. A well-structured program should combine ground-based and space-based observations in a mutually supportive way.

OTHER TECHNIQUES

Ground-based speckle-interferometric methods have already demonstrated their capability to detect objects smaller than main-sequence stars (brown dwarfs) in orbit around other stars. Such an object has recently been detected around the star Van Biesbroeck 8. Although this technique has not yet demonstrated a potential for detecting smaller, more typical planets, the method does provide a complementary technique for examining the systems (if any) associated with low-mass binary stars.

In space, instruments already being developed now or planned for the future can make important contributions to the detection and study of other planetary systems. The *Hubble Space Telescope (HST)*, scheduled for launch in the near future, will carry several instruments that can be used to detect extrasolar planets and brown dwarfs. The *HST*'s Wide-Field Camera has the capability to detect faint objects around other stars by blocking out the light from the primary star. The Faint Object Camera can possibly detect and image large extrasolar planets within ten to 20 parsecs of Earth, if the planets are at least the size of Jupiter and are sufficiently distant from their primary star. Using the Fine Guidance System, which has an accuracy of about one milli-arcsecond, the *HST* can make astrometric measurements comparable to the best from Earth and could, with long observations, detect the tiny movements produced in the positions of nearby stars by very large planets around them.

Beyond the initial *HST*, other instruments and missions, now in the planning and development stage, can also make important

Extrasolar Planets: Beginning a Search from Space

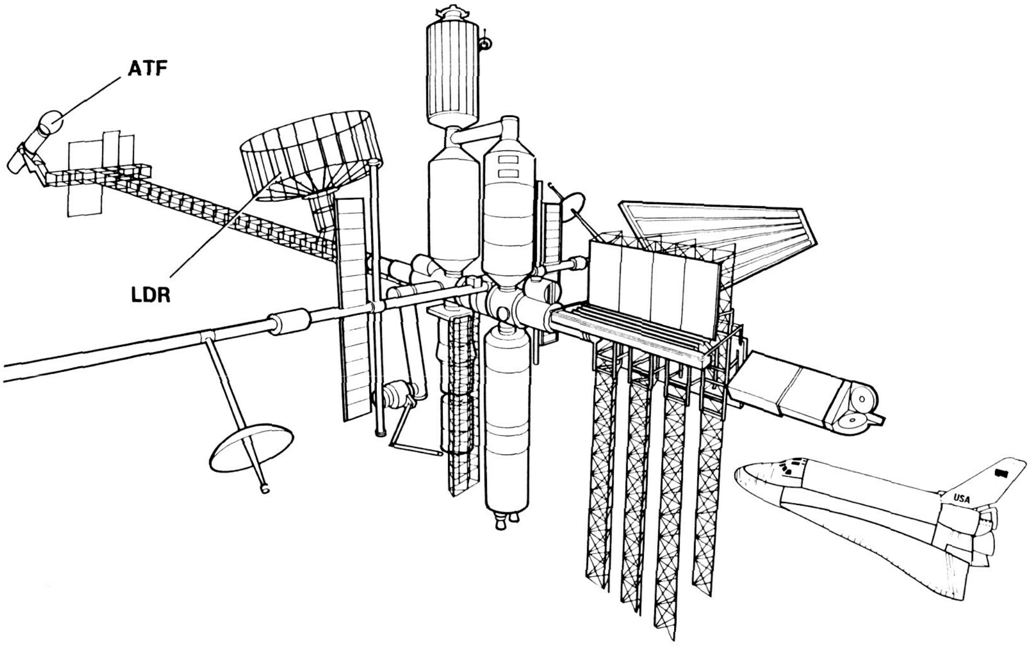
With the establishment of a permanent Space Station in orbit around Earth, the search for planets around other stars will take on a new dimension. New telescopes, permanently located above the blurring and distortion produced by Earth's atmosphere, can apply a variety of techniques to search for other planetary systems with a precision and sensitivity never before possible.

The first search technique to be carried into space may be an advanced method of *astrometry*, precise measurements of a star's position that can detect the gravitational influence of hidden planets. Already under study is a proposed *Astrometric Telescope Facility (ATF)*, a large telescope that could be externally attached to the Space Station to carry out a long-term and definitive search for other planetary systems.

The *ATF* would make ultraprecise measurements of the positions of about 100 nearby stars for 10 to 20 years. These measurements would be sensitive enough to detect the presence of other planets as small as Uranus and Neptune as far as 25 to 30 light-years away. Equally important, this space-based technique makes it possible to study a large number of stars, so that, if no planets are detected, this negative result will have a convincing amount of data behind it.

The *ATF* would be a telescope about 15 meters long, with a mirror about 1.5 meters in diameter, directly attached to the Space Station. Because of the need for many repetitive observations over long periods of time (10 to 20 years), the telescope will include a capability for a high degree of autonomous operation.

ASTROMETRIC TELESCOPE FACILITY ON SPACE STATION



NOTE: ATF IS ASTROMETRIC TELESCOPE FACILITY
LDR IS LARGE DEPLOYABLE REFLECTOR (ASSEMBLY ON SS)

contributions to the search. A group of second-generation instruments for *HST*, to be installed in the early 1990s, will include an infrared device that can search for brown dwarfs, as well as spectrometers that could possibly make radial-velocity measurements of nearby stars. Another instrument planned for the 1990s is the *Space Infrared Telescope Facility* (*SIRTF*), which will greatly extend the range and variety of infrared measurements from space, allowing us to study in more detail the areas of possible planet formation identified by *IRAS*. *SIRTF* will also have the capability to pursue other problems important to our understanding of star formation.

Ground-based imaging observations have considerable potential for improvement in the future through the increased use of low-scattered-light telescope design, active optical systems, improved coronagraphic masks, better detectors, and advanced image processing techniques. The feasibility of detecting planets by such means has not been demonstrated–even in principle–but it is clear that important studies of diffuse circumstellar matter are already within reach.

Beginning the Search

The questions of how the solar system formed, and whether it is unique, have been part of human thought ever since the beginnings of human society. These questions have been explained by religions, debated by philosophers, and finally attacked by scientific studies of the universe around us. In recent years, we have developed what seem to be good theories for the origin of our solar system, and we have found reason to believe that similar systems may exist around many other stars.

We are now poised to make serious attempts to answer the long-standing question of whether our solar system is unique. The necessary tools, and the places to put them, are at last coming within our reach. Now that we can carry instruments into space, we can eliminate the problems caused by Earth's atmosphere. A permanent presence in space, embodied by the planned Space Station, can support the long-term observations that must be made.

The problems of carrying out a search for other solar systems have become well-defined, as have many of the possible solutions. We need no major technical or scientific breakthroughs to make the search. We do need technical capabilities and support to achieve our goals for studying other planetary systems–detection, dynamic analysis, and imaging. We need to study astrometric methods and the planned Space Station in particular detail, because it now seems appropriate to begin our search with astrometric measurements made from the Space Station. At the same time, we need to continue ground-based research in order to study other possible planetary systems as best we can, to define better the problems and the needed developments, and to develop new and better instruments for space observations.

In some ways, the active search for other planetary systems has already begun. There is more evidence for the existence of other

planetary systems now than there was a decade ago, although the evidence is still only suggestive and tantalizing. The observations made from *IRAS*, the detection of a brown dwarf from the ground, and the improvement of our own theories of solar system formation, have developed a sound framework for the search. Even so, we have not yet detected anything like a familiar planet or a planetary system around any star, and we need to find such objects (or establish that they are absent) before our theories can be tested. When we can take the necessary instruments into space, the search can begin in earnest.

A search for other solar systems will make major discoveries, no matter how it turns out. If we find–as most scientists now expect–that worlds are common around other stars, then we can be confident of our theories and perhaps more confident that life exists elsewhere in the universe. If we find no other worlds, then we must strive to explain why our own cosmic neighborhood is a freak of nature, to understand the unique quirk of the universe that produced us, and to face the real possibility that we are in fact alone. The questions of other planets and other life are closely linked, and the search for one is in many respects a search for the other.

CONCLUSIONS

1. The ideas that our solar system is not unique, and that there are similar planetary systems around other stars, are supported by theoretical considerations and by a small amount of suggestive observational data. However, the definite verification or disproof of those ideas is an essential step in increasing our knowledge about the formation of stars, the origin of planetary systems, and the development of life in the universe.

2. Theoretical models developed for the origin of our own solar system involve the gradual collapse of a cloud of gas and dust (the *protosolar nebula*) into a Sun and planets in response to the interactions of several forces–self-gravity, and dissipative and frictional mechanisms in the denser parts of the cloud. The observed regular features of our own solar system suggest that this process was neither random nor chaotic. The mechanisms do not appear unique, and similar processes should occur during formation of a large number of other stars.

3. The time is ripe to consider specific projects for the detection and study of other planetary systems. The combination of theoretical models for planetary formation, advancing technology, and the ability to carry out long-term observations (on the order of decades) above Earth's atmosphere makes such searches feasible for the first time in human history.

RECOMMENDATIONS

1. Activities involving the search for, and the study of, other planetary systems, should be carried out by NASA's Solar System Exploration Division. These activities are consistent with the Division's established goals and especially with the goal of understanding the origin and evolution of our own solar system.

2. In order to provide results that are both reliable and scientifically significant, a search for other planetary systems should be capable of: (a) examining approximately 100 single stars over a distance of about ten parsecs from the Sun; (b) detecting the presence of extrasolar planets with masses as low as those of Uranus and Neptune; (c) lasting at least ten to 20 years.

3. In the next few years, some major astronomical facilities, such as the *Hubble Space Telescope (HST)* and the *Space Infrared Telescope Facility (SIRTF)* are planned for launch into Earth orbit. The outstanding capabilities of these facilities for astronomical observations can also be used to make important contributions to the search for other planetary systems, and to research on the formation of stars and planetary systems, and they should be used for such investigations to the maximum extent possible. NASA and the Solar System Exploration Division should establish the coordination mechanisms needed to ensure that the opportunities to use these facilities to detect other solar systems, and to provide important technical data for future projects, are not missed.

4. Future projects for the detection of other planetary systems should involve the use of the Space Station and the associated technical infrastructure that will be established in Earth orbit in the mid-1990s. These new capabilities will make possible in Earth orbit the long-term measurements required for detection of extrasolar planets.

5. It seems now that the most feasible and best-suited technical approach to planetary detection in the near future is a space-based astrometric telescope which can measure stellar positions to an accuracy of 10^{-5} seconds of arc. Such measurements can not only detect other planetary systems but can also provide unique information about their structure and dynamics. This concept, which is now under study, should be examined in more detail in order to develop it as a possible experiment for the Initial Orbital Capability (IOC) phase of the Space Station.

6. A variety of other potential detection mechanisms exists and should also be examined in detail. Attention should be given to the complementary techniques of direct detection (i.e., imaging) and indirect detection (astrometry, photometry, *et al.*).

7. Additional techniques should be studied in detail for possible use in second-generation searches. These include: astrometry using interferometry, imaging techniques based on low-scattered-light instrument development, and optical interferometry. In addition, appropriate ground-based investigations, based on such techniques as radial-velocity measurements, astrometry, and other methods, should be supported.

The JPL six-wheeled surface roving vehicle is a prime candidate for use on Mars.

8. New Tools for New Worlds

TECHNOLOGY NEEDS FOR THE AUGMENTATION MISSIONS

"Give Us the Tools..."

The selection and planning of Augmentation Missions cannot be separated from the many issues involving the development of future technology. The reason is simple: **none of the Augmentation Missions can be carried out with currently available technology.** In short, in order to obtain rich new yields of scientific information, we must develop new tools.

The SSEC regards this close relationship between Augmentation Missions and new technology development as a healthy situation. Historically, one of the needs (and one of the major benefits) of space exploration has been the continuing development of new

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technologies which then find widespread application beyond the specific space programs for which they were developed.

The Augmentation Missions described in this report are a natural and desirable continuation of this historical trend. One of the intentions of the Augmented Program is to drive technology development by including missions which provide major technical challenges as well as exciting scientific discoveries.

The technological drive provided by the Augmentation Missions has three components:

1. The identification and development of specific technologies needed to carry out individual Augmentation Missions;
2. The application of these technologies, once developed, to other Augmentation Missions, especially to candidate missions for the period after 2000, and to more general space activities;
3. The application of generic technologies originally developed for Augmentation Missions (e.g., new propulsion systems, robotics, radiation-resistant instrument components) to areas outside planetary exploration and even outside NASA, so that these new technologies provide a general benefit to the nation.

This chapter emphasizes the first of these aspects, the identification of specific technologies needed for particular Augmentation Missions. Because many of these technologies are generic, some discussion of their application to future Augmentation Missions is also included. The third aspect, which involves the more general economic and policy issues, does not lie within the scope of the SSEC and is not addressed in further detail in this report.

This chapter is not intended to discuss in detail all the necessary and desirable new technologies required for a wide range of future space activities. Therefore, the following conventions have been used to structure the discussion:

1. Technological needs have been identified from the specific operational requirements for individual Augmentation Missions.
2. Detailed consideration has been given only to unmanned Augmentation Missions identified as candidates for the period before the year 2000, i.e., the *Mars Sample Return* and the *Comet Nucleus Sample Return*. This restriction still leaves a broad and adequate base for discussion, for two reasons: (a) both missions require a wide range of new technological developments; (b) many of the technologies needed for sample return missions are equally important for other Augmentation Missions, particularly missions to the outer planets.
3. Possible solutions and alternatives to these technical needs are indicated, but are not examined in detail. Follow-on studies for these solutions should be carried out in the near future by more specialized groups.

4. Some discussion of specific technology needs for Augmentation Missions that clearly lie in the post-2000 period has been included for the sake of completeness and in order to identify specific long-lead-time items for which development should start in the near future.
5. The development of new instrument technology has not been considered in detail. It is assumed that some instrument development will be carried out, either as an element of the Core Program or outside the Core Program entirely. Moreover, to a considerable extent, new instrument developments are not as critical to the Augmentation Missions as are the other technologies discussed here.
6. Separate brief discussions are provided for two topics related to, but not specifically a part of, Augmentation Missions: technology development for the evaluation and use of nonterrestrial resources, and the possible use of the Space Station to support Augmentation Missions.

Critical Technologies for Sample Return Missions

Specific technology requirements can be identified by considering the goals for two near-term Augmentation Missions, the *Mars Sample Return* and the *Comet Nucleus Sample Return*. In comparison with the needs of Core Program Missions, these requirements include:

- Heavier, more complex payloads;
- Precise landings;
- Automated orbital rendezvous and docking maneuvers;
- Extended automated surface mobility;
- Complex sample collection, handling, and preservation capabilities.

Although these requirements have been generated by considering only sample return missions, they are in fact very general, and the technical solutions are expected to be applicable to a wide range of possible Augmentation Missions. Many of the requirements, such as improved propulsion, aerocapture, and orbital rendezvous and docking, are even more general; their development, as well as their major applications, may fall in areas far outside the scope of the Solar System Exploration Division. **In these cases, the Solar System Exploration Division should make its detailed mission requirements continually available to the organizations charged with the development of these technologies, in order to ensure that the final form of the developed technology is compatible with, and can support, sample return missions and other Augmentation Missions.**

Critical technologies needed are discussed in more detail below. They include: more capable propulsion systems, aerocapture, aeromaneuvering, automated rendezvous and docking systems, automated surface roving vehicles, and automated sample collection and handling techniques.

The requirements, and the technological needs that they generate, are discussed in more detail in the following sections. In each section, the discussion includes the following points: reason for the critical requirement; inadequacy or nonexistence of current techniques; possible technical solutions; benefits of the solution to the specific Augmentation Missions; and the long-term value of the solution to future (post-2000) Augmentation Missions.

Getting There (Propulsion)

The most common characteristic of all the Augmentation Missions is the need to transport heavy and sophisticated scientific payloads to a variety of distant worlds. To make this possible, improved propulsion and launch capabilities are essential. The most powerful launch combination now available for planetary missions, the *Shuttle/Centaur*, cannot accommodate *any* of the currently considered Augmentation Missions in a single launch, unless other advanced technologies become available. The *Mars Sample Return* mission becomes possible only if on-orbit assembly and/or on-orbit fueling can be carried out to enhance the basic *Shuttle/Centaur* capabilities. The *Comet Nucleus Sample Return* also cannot be done without advanced launch capabilities or advanced spacecraft propulsion, and the same is true for any Augmentation Missions to the outer planets.

To make Augmentation Missions possible, new propulsion techniques must be developed to enhance the available *Shuttle/Centaur* capabilities. There are several ways in which such improvements might be achieved. One possibility is *solar-electric propulsion (SEP),* in which electricity obtained from solar panels is used to ionize a heavy element like mercury. The stream of ions, ejected from the spacecraft, produces a continuous low thrust which can, over long periods of time, accelerate a spacecraft to high velocities.

SEP would be especially valuable for long missions within the inner solar system, where solar panels can provide an efficient source of power. SEP has been identified as a critical enabling technology for the *Comet Nucleus Sample Return* mission discussed earlier, and the technique has been under study and development for more than a decade.

A related technique, *nuclear-electric propulsion (NEP)*, uses a nuclear reactor to provide the electric power needed for ionization. Although not as advanced in development as SEP, NEP could be an alternate propulsion method for the *Comet Nucleus Sample Return.* NEP would be even more valuable for missions to the outer planets, which lie too far from the Sun for solar panels to generate enough electricity to operate the low-thrust engines.

There are other possibilities for obtaining increased propulsion capability for Augmentation Missions. Enhancements provided by on-orbit operations at the Space Station, which will be available in the 1990s, have already been discussed in connection with the *Mars Sample Return* mission. Similar operations, discussed in more detail below, could make other Augmentation Missions possible.

The most immediate and obvious benefit from the development of new and improved propulsion technologies is that the *Comet Nucleus*

Required Technology for Augmentation Missions

MSR = MARS SAMPLE RETURN CNSR = COMET NUCLEUS SAMPLE RETURN

REQUIREMENT	PROBLEM WITH CURRENT TECHNOLOGY	PROPOSED SOLUTION
To reach target body with adequate mass, using *Shuttle/ Centaur (CNSR)*	• *Shuttle/Centaur*–inadequate for launch and rendezvous *(CNSR)*	• *Low-thrust propulsion* -SEP, NEP • *Space Station capabilities:* - On-orbit fueling - On-orbit assembly - Stage clustering
Orbit insertion around target planet Mars: *MSR* Earth: *MSR, CNSR*	• *Retropropulsion*—fuel and weight requirements inadequate for required payload	• *Aerocapture*–insertion by atmospheric penetration - Lifting body aeroshells (biconic lifting-brake) - Autonomous guidance/navigation system - Aerodynamic, aerothermic research
Accurate landing on target planet *(MSR)*	• *Ballistic entry*–large target ellipse, restricted access to scientifically important areas	• *Aeromaneuver*–autonomous flight-control guidance system
Orbital rendezvous and docking *(MSR)*, and zero-G rendezvous and docking with small body *(CNSR)*	• Does not exist (except U.S.S.R. *Progress* vehicles, Earth orbit)	• *Automated, autonomous rendezvous and docking techniques* - On-board guidance and navigation systems sensors - Range and bearing systems - Command/control systems - At comet: docking, grappling techniques
Sampling mobility (Mars): Need to reach variety of sites, need to travel from landing site to scientific sites	• Does not exist	• *Automated, semiautonomous roving vehicle* - Mobility, articulation, manipulation - Limited autonomous operation - Support sample collection, preservation, manipulation systems - Support limited science observations for sample characterization, selection - Autonomous control–perception, diagnosis, actuators
Secure appropriate samples *(MSR, CNSR)* • Secure samples • Manipulate, document, store, preserve • Diverse range of materials–rock, soil, dust, air, ice • Variety of operations	• Does not exist	• *Remote sample techniques* (diverse) - Acquisition, manipulation, grasp, scoop, drill - Containment and preservation techniques - Sample transfer techniques - Semiautonomous operation; interaction with sample characterization instruments

BENEFITS	FUTURE MISSIONS (ENABLE OR ENHANCE - POST-2000)
• *CNSR* mission enabled • Increased payload • Permits emplaced long-lived surface station	• Mercury orbiter/lander • Venus lander or atmospheric station
• *MSR* mission possible with single *Shuttle/Centaur* • Payload includes surface rover for required mobility	• Outer planet orbiter/probes • Outer planet landers (Titan, Galilean satellites)
• Capability to land close to prime scientific sites (within rover range) • Access to candidate sites increased	• Venus lander • Titan lander
• *MSR* mission enabled • *CNSR* mission enabled	• Asteroid sample return
• *MSR* mission enabled • Limited surface science possible on rover during sampling phase • Long traverse science (with sample characterization instruments) possible after sampling phase	• Mars science rover traverse • Moon, Mercury surface rovers
• *MSR* mission enabled • *CNSR* mission enabled • Scientific yield increased by ability to collect, subdivide, manipulate–(more samples for given payload)	• Asteroid sample return • All other sample returns—Mercury, Venus, Galilean satellites

Low-Thrust Propulsion: Making Haste Slowly

To send a spacecraft out of the gravitational field of one world and into the gravitational field of another, the spacecraft must provide a large enough force (thrust) for a long enough period of time. But often the same trip can be made in two basically different ways: by providing a large thrust for a short period of time (as with a rocket motor) or by providing a small thrust over a much longer period of time.

The amount of thrust, and the length of time that it can be applied, depend on the nature of the rocket motor and the amount of fuel that it carries. A convenient measure for comparing rocket motors is the *total impulse,* which is equal to the *propellant mass* carried by the rocket multiplied by the *exhaust velocity,* the speed at which the products of combustion are driven backward from the rocket, thus driving the rocket forward.

Chemical rockets, long used to send objects into orbit and to launch the *Apollo* astronauts toward the Moon, are limited in the exhaust velocities they can attain because of the fixed amount of energy that can be released by the combustion process. A major advantage of *electric propulsion* over chemical propulsion is that the limiting exhaust velocities are much higher, which means that less propellant is required to produce the same total impulse.

The idea of electric propulsion actually goes back to the beginning of modern rocketry itself. As early as 1906, Dr. Robert Goddard, the famous American rocket pioneer, realized that chemical propulsion rockets were limited in exhaust velocity, and he suggested that this limitation might be overcome if a "propellant" of electrically charged particles could be accelerated to very high velocities.

Today's electric propulsion systems work on the same ideas proposed by Robert Goddard. In such systems, electric or magnetic forces are used to eject a "propellant" of charged atomic particles; the electric power needed is supplied to the propellant by a separate power source. Electric propulsion systems, unlike rockets, are the only ones in which the power source is totally separated from the thrust-producing element. This separation makes it possible for an electric rocket to eject its propellant at much higher velocities than a chemical rocket, thereby obtaining more thrust per pound of propellant used.

Despite this advantage, electric propulsion systems have a major problem: the total thrust obtained is less than the weight of the motor because the required electric power plant is very heavy. For this reason, a totally-electric propulsion system would–literally–never get off the ground, and electric propulsion can only be used after the spacecraft has been launched into orbit. Another problem is that an electric system must operate much longer to produce the same total impulse that a chemical rocket can provide in a short period of time.

Even with these limitations, however, electric propulsion systems can carry out many important planetary missions in the same length of time required with chemical rockets. Furthermore, such missions can be carried out with much lighter vehicles, because the weight of "fuel" needed for an electric propulsion system is much less than required for a chemical rocket.

The real usefulness of electric propulsion in planetary exploration is for missions that require large payloads, long travel times, or a combination of both. For such missions, chemical propulsion is inadequate, and the advantages of electric propulsion become overwhelming.

Electric propulsion systems *(thrusters)* come in three types: *electrothermal, electromagnetic,* and *electrostatic.*

1. In the *electrothermal thruster,* electric power heats the propellant (a gas) to a high temperature by passing an electric arc through it (an *arcjet*) or by passing the gas over surfaces heated by electricity (a *resistojet*). This type of thruster is similar in some respects to a chemical rocket; there is no combustion, but the resulting hot gases are also expanded outward through a nozzle to produce thrust. This type of rocket can produce exhaust velocities higher than those of chemical rockets because more energy can be added to the gas molecules by heating than can be made available by chemical combustion. However, the amount of energy obtained is limited by several factors, including the dissociation of the gas at high temperatures and the possible failure of solid parts of the system under the extreme heating necessary. For these reasons, these devices will probably not be used for interplanetary missions, but they could be used as attitude-control devices for satellites in Earth orbit.

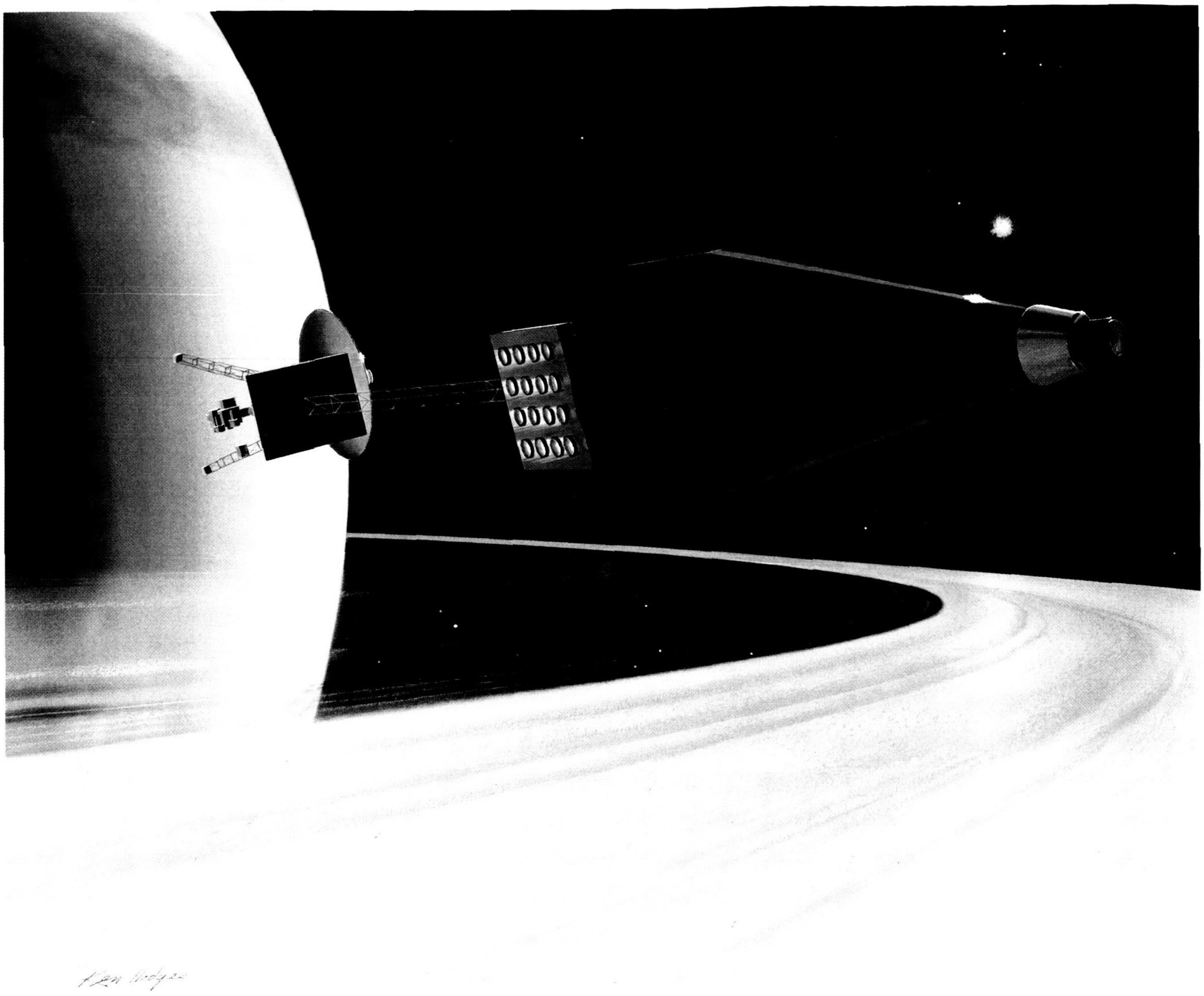
2. In the *electromagnetic thruster* (also called the *plasma thruster*), the propellant gas is ionized (by removing an electron from each atom) to form a plasma of charged particles. This plasma is then accelerated rearward by electric and magnetic fields. One version, the magnetoplasmadynamic (MPD) arc thruster, is one of the most promising concepts for this type of thruster. A particular advantage for planetary missions is that it can use a low-voltage, high-current source, and it can therefore use conventional solar-cell power systems directly with little additional equipment.

3. The *electrostatic thruster* (or *ion engine*) is similar to the electromagnetic thruster; in both devices, the propellant atoms are ionized. However, in the electrostatic thruster, the electrons are continuously removed from the ionization region at the same rate at which the new ions are accelerated rearward, thus generating a continuous flow that produces an accelerating back-reaction on the engine. The most successful version of this type of thruster is called the electron-bombardment thruster. In contrast to electromagnetic thrusters, electrostatic thrusters are high-voltage, low-current devices that cannot be easily adapted to solar-cell power systems without accessory equipment. However, they are more efficient than electromagnetic thrusters and can produce higher levels of thrust.

All of these thrusters require electric power to operate, and the two basic sources for such power on a spacecraft are the Sun (through solar-cell panels) and nuclear reactors. *Solar-electric propulsion (SEP)* systems can operate only in the inner solar system, because the light intensity available to operate the solar panels decreases rapidly with distance from the Sun. SEP is therefore an attractive method for missions flown within 500 million kilometers of the Sun, or well within the orbit of Jupiter. SEP could also be used near the Sun as a "boost stage" on a mission intended to go further out.

The great potential of *nuclear-electric propulsion (NEP)* systems is that the power available to drive the engine is independent of distance from the Sun, and NEP systems can provide useful thrust in any part of the solar system. This feature makes NEP especially valuable for missions to the distant outer planets, because it can be used to slow the spacecraft near the target planet. An outer planet orbiter, for example, could use a NEP system to slow down and enter the desired orbit while consuming only a small amount of propellant.

Nuclear-electric propulsion concept for a mission to Saturn's rings.



Sample Return, a critical element of the Augmented Program, becomes possible. Better propulsion will also benefit the whole range of planetary exploration; worlds now inaccessible could be reached, and exciting Augmentation Missions could be designed to explore further those worlds barely reached by Core Program Missions. With improved propulsion techniques, such missions as orbiter/probes to Uranus and Neptune, a Mercury orbiter/lander, or a Venus sample return, become concrete possibilities rather than hopeful dreams.

Stopping (Orbital Insertion)

The ability to slow down from a heliocentric orbit and to enter a desired orbit around a target planet is a basic requirement for virtually all Augmentation Missions. The *Mars Sample Return* mission, for example, requires two such orbit insertions. First, the spacecraft must enter orbit around Mars, and later, the Sample Return Capsule must safely enter orbit around Earth to await

recovery. The *Comet Nucleus Sample Return* mission has a similar need for its Sample Return Capsule to enter Earth orbit.

The current technique for orbit insertion is retropropulsion, the use of rocket motors to provide the force needed for braking and insertion. This technique, although reliable and long-used, carries significant weight penalties because both the rocket motor and its fuel must be launched from Earth and carried to the place where they will be used. These penalties are illustrated in the earlier discussion of various possible propulsion systems for the *Mars Sample Return* mission *(see Chapter 3)*.

For planetary bodies with atmospheres, a more efficient alternative to retropropulsion is *aerocapture*. In such a maneuver, the spacecraft makes its first encounter of the planet by entering the atmosphere on a precisely selected course, using atmospheric resistance to reduce its original velocity so that, when the spacecraft leaves the atmosphere, it will remain in orbit around the planet. Subsequent atmospheric encounters can be made to modify the initial orbit to a desired final one.

Aerocapture has not yet been used in planetary exploration, and considerable development is needed in several areas before the technique can be used. These areas, which involve both basic research and technology development, include:

- Design and development of appropriate lifting-body aeroshell shapes for the spacecraft;
- Development of autonomous guidance and navigation systems to ensure precise control during atmospheric passage;
- Basic research on improved aerodynamic and aerothermic solutions to the aerocapture environment.

The successful development of aerocapture techniques will be a major contribution to the success of a variety of Augmentation Missions. The *Mars Sample Return* then becomes at least marginally possible with a single *Shuttle/Centaur* launch, and its payload can include a surface roving vehicle for sampling operations and for post-sampling science exploration on the martian surface. The *Comet Nucleus Sample Return*, no longer needing a retropropulsion system for its Earth Return Capsule, can carry an increased payload, possibly including a long-lived surface station to be left on the sampled comet.

Study of the outer planets will also receive a major boost from the development of successful aerocapture techniques. Such capabilities are a key step toward many important missions–e.g., orbiter/probe missions to Uranus and Neptune, and landers or atmospheric buoyant stations to Titan.

Getting to the Right Spot (Targeting)

For sample return missions, and especially for the *Mars Sample Return*, precise landings are critical. A relatively small deviation (as little as 50 to 100 kilometers) from the intended landing site may place the spacecraft in a totally different area, one which may be

"...Through the Air With the Greatest of Ease...": Aeromaneuvering for the Planets

Planets with atmospheres provide a special potential benefit to mission planners. The artful use of a planet's atmosphere can help solve two fundamental problems: how to get a fast-traveling spacecraft into orbit around the planet, and how to get a lander out of orbit to the right point on the planet's surface.

To carry out such operations successfully, kinetic energy must be removed from the spacecraft, and forces must be carefully applied to control its movements. Traditional techniques, applied to airless objects like the Moon, use rocket motors (retropropulsion systems), which are heavy and require large amounts of fuel. The development of *aerocapture* and *aeromaneuvering* techniques will make it possible to carry out the same operations much more economically.

The idea of using an atmosphere to intentionally modify the orbit of a spacecraft has a long and varied history that goes back to the first serious proposals in the early 1960s. Various studies since then have considered how a spacecraft might pass through an atmosphere in order to change the size, shape, or inclination of its orbit. Despite the wide range of possible applications, few actual orbital experiments have been performed, with one notable exception: atmospheric drag has been used to provide controlled, nondestructive reentries for every manned mission from *Project Mercury* to the *Space Shuttle,* and similar entry techniques have been successfully used for unmanned spacecraft at Venus, Earth, and Mars.

A wide variety of vehicle shapes and sizes have been studied for possible use in the atmospheres of Earth and other planets. Despite the variety, they can be grouped according to their *lift-to-drag (L/D) ratio,* a quantity that compares the two chief forces (lifting and retarding) that the atmosphere exerts on them. The designs studied to date fall into three categories of L/D: low, high, and moderate.

1. The **low L/D vehicle** designs tend to resemble the early *Mercury* and *Apollo* space capsules. They use flat plates or spherical caps as shields for aerobraking, a design feature that makes them adaptable to existing spacecraft designs and simplifies the underlying spacecraft structure needed to support large shields.

2. The **high L/D vehicle** designs look more like the *Space Shuttle Orbiter.* They have a more conventional streamlined shape, usually that of a delta-wing aircraft or a flattish *lifting body.* These

shapes generate a high lift in the atmosphere, making possible a slow descent and more maneuvering time. Such a vehicle, in the process of descent, can vary the descent rate significantly and can also maneuver at an angle to its descent path if necessary.

3. **Moderate L/D designs,** like the high L/D concepts, also use streamlined shapes, but they are less winglike. Some designs are cylindrical, others have a *biconic* shape like parts of two cones attached together. Both designs carry a tilted elliptical shield for aerobraking maneuvers in the atmosphere.

For interplanetary missions, two types of vehicles have been studied, each of which uses different procedures to enter an orbit around a planet. In *aerobraking,* a conventional rocket retropropulsion motor is used to place the vehicle in a highly elliptical orbit, part of which passes through the upper part of the atmosphere. Repeated passes through the atmosphere slow the vehicle down enough to place it into a lower and more circular orbit.

A second type of vehicle is intended for *aerocapture,* a procedure in which the spacecraft makes a single pass through the atmosphere on its approach to the planet. The atmospheric drag slows the spacecraft enough for it to enter orbit around the planet, and no rocket retropropulsion system is needed. Designs for such vehicles currently involve a biconic shape with a moderate L/D ratio.

Aeromaneuvering techniques provide several important advantages for planetary missions: flight times can be shortened, and a larger payload inserted into the desired orbit around the planet. These techniques can help open up a wide range of worlds with atmospheres to advanced future planetary missions: the planets Venus, Mars, Jupiter, Saturn, Uranus, and Neptune, and the large moons Titan (around Saturn) and possibly Triton (around Neptune). (Sample return missions returning to Earth can also use aerocapture to place the return vehicle in the proper orbit to make recovery possible.)

It should be noted that detailed studies have shown that applying aerocapture directly at Jupiter and Saturn provides no advantage over conventional methods. For these huge planets, there is too much danger of excessive heating of the spacecraft, and the successive orbits take too long to change to the desired ones. However, aeromaneuvering can still be applied in the Saturn system by using the atmosphere of Titan instead.

much less scientifically desirable. As a result, the most optimum samples may not be obtained, or most of the mobility and resources of the rover will be expended in attempts to reach the correct site.

The targeting situation for the *Comet Nucleus Sample Return* is significantly different. The sample location is not as critical, and it is not necessary to select the landing site in advance of the mission. Furthermore, because of the low gravity of the comet, the "landing" maneuver is actually a slow rendezvous and docking, which can be controlled at short range.

Current ballistic-entry techniques for Mars and other planets with atmospheres, like those used for the *Viking Landers*, have undesirably large landing uncertainties. (For the *Viking Landers*, the "target ellipse," i.e., the best estimate of the location of the eventual landing, was about 50 kilometers by 120 kilometers in size.) More precise techniques for guidance and targeting are essential if the desired landing site is to be reached.

One solution for more accurate entry and landing is to develop the capability for *aeromaneuvering*. Such techniques make it possible to actually change direction while passing through the atmosphere in order to land exactly on a preselected site. This capability requires several related technological developments: an autonomous flight-control system, a suitable aeroshell with control mechanisms for the lander, terrain-matching capabilities for continuous course correction, and perhaps even specially designed entry vehicles and totally new techniques for final descent.

The benefits of aeromaneuvering capabilities can be seen in the *Mars Sample Return* mission. Using aeromaneuvering instead of traditional ballistic-entry methods, the entire planet, rather than just the zone below 45 degrees north latitude, becomes accessible to a sample return lander. In addition, the landing error can be reduced to perhaps ten to 20 kilometers, increasing the chances of being able to sample the most desirable sites with the Rover.

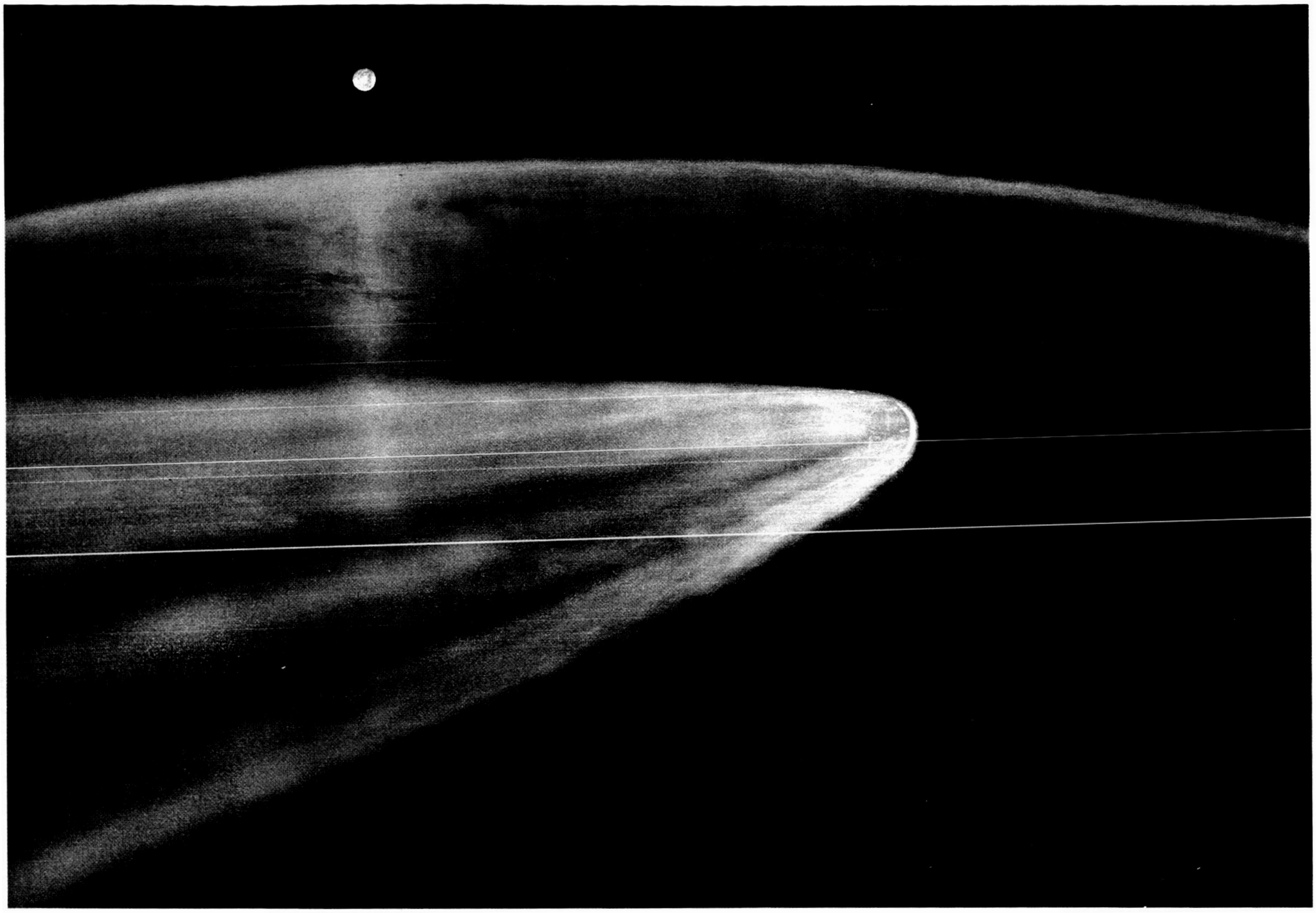
Aeromaneuvering technology is also a major benefit to any Augmentation Mission aimed at a world which has an atmosphere. Such technology would increase the capabilities and scientific value of–to pick two widely separated examples–a Titan lander or a Venus lander.

Getting It All Together (Orbital Rendezvous and Docking)

Sophisticated orbital rendezvous and docking techniques, suitably automated, are needed for both sample return missions. For the *Mars Sample Return* mission, Mars-orbital rendezvous and docking after sample collection are essential so that the loaded Sample Return Capsule can be transported from the martian surface and transferred to the Earth Return Vehicle. The *Comet Nucleus Sample Return* has a similar requirement: in the current mission design, the loaded sample collecting stage must lift from the comet and rendezvous with the parent spacecraft at some distance from the comet after the sample has been collected.

In addition, the *Comet Nucleus Sample Return* has a unique

A spacecraft returning to Earth uses aerocapture technology to go into orbit around Earth.



"rendezvous and docking" requirement of its own. Because of the extremely low-gravity environment of the comet, the "landing" on the comet will closely approximate an orbital rendezvous, and unique technical solutions are needed to the problems of "landing" the sample collecting stage on the comet and anchoring it in place.

Technologies for automated rendezvous of unmanned vehicles are largely nonexistent and have never been used in planetary missions. The only current example is the U.S.S.R. *Progress* unmanned spacecraft, which can rendezvous and dock with the currently orbiting U.S.S.R. *Salyut* and *Mir* space stations.

To obtain the necessary autonomous orbital rendezvous and docking techniques requires several related technical developments: on-board guidance and navigation systems, range and bearing sensors, command and control systems, appropriate docking mechanisms, and (for the *Comet Nucleus Sample Return*) anchoring or grappling techniques for fixing the sampling device to the surface of the comet.

The major benefits of autonomous rendezvous and docking techniques are immediately obvious. The *Mars Sample Return* mission, with its need for orbital rendezvous and sample transfer, becomes possible. The *Comet Nucleus Sample Return* mission, which needs at least one and possibly two such maneuvers (one to dock on

the comet and the other to transfer the sample to the Earth Return Capsule) also becomes possible.

Such capabilities will be applicable to a wide variety of other missions, especially those involving sample return. In particular, the techniques developed for the *Comet Nucleus Sample Return* will be directly applicable to future sample return missions to the asteroids.

Getting Around (Surface Mobility)

Surface mobility is critical to the *Mars Sample Return* mission. The type of mobility enabled by a rover is essential to reach key sampling sites, to collect a wide variety of sample materials, and to conduct surface science investigations over a wide area.

Current capabilities for surface mobility by means of an automated rover have not yet been demonstrated; such vehicles have never been used in the U.S. space program. The only automated rovers to be operated on another planetary surface were the U.S.S.R. *Lunakhods* on the Moon in the early 1970s.

Provision of this essential capability for the *Mars Sample Return* mission requires a large number of related technical developments that can be combined to produce the desired vehicle–a fully autonomous or semiautonomous robot rover which is able to travel the desired distance and which carries devices to both document and collect samples. Essential components of such a vehicle include:

- Systems for mobility, articulation, maneuvering, and navigation;
- Subsystems for sample observation, characterization, manipulation, acquisition, documentation, storage, and preservation;
- Capability for some degree of autonomous operation;
- Autonomous control: subsystems for perception and diagnosis, linked to appropriate actuators.

There is a continuing debate about how "smart" such a vehicle should be. Should it incorporate state-of-the-art robotics developments ("artificial intelligence") to make it capable of virtually independent long-term operation, or should it be a relatively "dumb" device dependent on frequent interaction with an Earth-based control? Because of the critical role of the rover in the *Mars Sample Return* mission, detailed studies should be instituted as soon as possible to decide this question, to define the other performance requirements, and to undertake the necessary technical developments.

The obvious benefit from the development of such a roving vehicle is that a cost-effective, scientifically productive *Mars Sample Return* mission, of the type discussed earlier, becomes possible. The rover is essential for mobility and sample characterization. Furthermore, the rover can be used for limited surface science during the sample collection phase. Afterward, the rover can be dedicated to longer surface traverses, employing the same instruments used for sample characterization.

Development of such a rover will benefit more than just the *Mars Sample Return* mission. A similar vehicle could be used in subsequent

Mars missions (not involving sample return) to provide extensive and long-distance surface science. Related rovers, based on the same technology, could be generally used in sample return missions or in science traverse missions to any moderate-gravity world (Mars, the Moon, Mercury, and–with considerable modification–perhaps Venus or the moons of Jupiter).

Getting the Right Stuff (Sample Collection)

No sample return mission can be carried out unless the right samples can be collected and returned to Earth. To accomplish this, it is necessary to carry out several complex operations: identification of samples, characterization, selection, manipulation, storage, documentation, and preservation. These challenges are increased by the large number of different sample materials that must be collected, often from a single site. Candidate sample materials include: solid bedrock, weathered bedrock, duricrust, loose soil, dust, ice, and atmospheric gases. Sample acquisition requires an equally complex range of operations: chipping, drilling, hammering, scooping, sieving, etc.

No current technology now exists to carry out these operations on planetary surfaces. Sample collection in the U.S. space program was carried out by astronauts on the Moon and to a limited extent by the stationary *Surveyors* on the Moon and the *Viking Landers* on Mars. Automated planetary sampling is limited to the U.S.S.R. *Luna 16, 20,* and *24* spacecraft, which drilled into the loose lunar "soil" at three locations on the Moon and returned the samples to Earth in the 1970s.

There is, therefore, a critical need to develop the means to carry out a variety of remote sample collection operations before any sample return missions can be done. These operations include:

- Identification, location, and characterization of possible samples;
- Decisions about whether to collect or discard a candidate sample;
- Acquisition and manipulation of the sample (grasping, chipping, drilling, hammering, scooping, sieving, etc.);
- Handling, documentation, and transfer techniques to provide for movement and tracking of the sample through the spacecraft and within the sample return capsule;
- Containment and preservation techniques to maintain the sample in a desired environment within the spacecraft;
- Semiautonomous operations, including interaction of the sample collection systems with the sample characterization instruments mounted on the rover.

The benefits from such developments are clear–they make the *Mars Sample Return* mission and (to a lesser extent) the *Comet Nucleus Sample Return* mission possible. Furthermore, the scientific yield of these missions will be significantly increased by the ability to characterize, select, subdivide, and manipulate samples on the spot. With these abilities, more samples, more diverse samples, and more

Sample Collecting on Mars: A Roving Commission

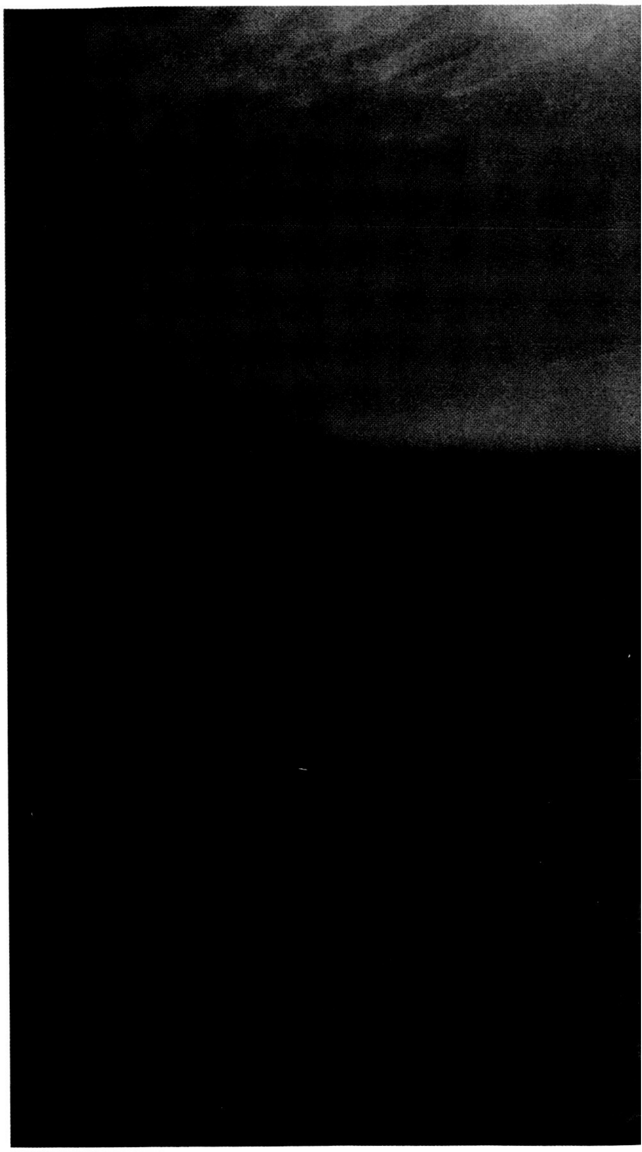
A major problem in planning a *Mars Sample Return* mission is that the most scientifically interesting sites are also the most hazardous to land in. The Tharsis volcanoes could provide important clues about the history and internal structure of Mars. The great chasms like the Valles Marineris expose huge slices of geologic stratigraphy and history in their walls. The winding fluvial channels and the polar ice caps may contain clues to past martian life or even samples of extant biota.

But these areas also contain many dangers for landing spacecraft–rocky terrain, large boulders, steep slopes, or loose materials. To investigate such a site, it is necessary to land at the nearest safe area and then send a roving vehicle out to the site for sampling and scientific studies. Using such a vehicle, observations can be made, and samples collected, at distances of tens of kilometers from the landed spacecraft, and a wide range of exciting science becomes possible.

The idea of autonomous roving vehicles originated in the 1960s. In 1970 and 1973, the U.S.S.R. *Luna 17* and *21* missions landed roving vehicles on the Moon. These *Lunakhods* traversed the lunar surface, returned TV pictures, and made analyses of the surface as they went. They were *semiautonomous rovers,* meaning that they carried out their operations in response to direct communications and commands from Earth.

More recently, the Jet Propulsion Laboratory and Ohio State University (under the Department of Defense's DARPA Program) have been conducting extensive investigations on various types of rover configurations. Three concepts have been extensively evaluated and are the prime candidates for Mars missions. They are: (1) a six-wheeled Lunar Roving Vehicle (LRV); (2) the Elastic Loopwheel Mobility System Vehicle (ELMS); (3) various walking (as opposed to rolling) vehicles.

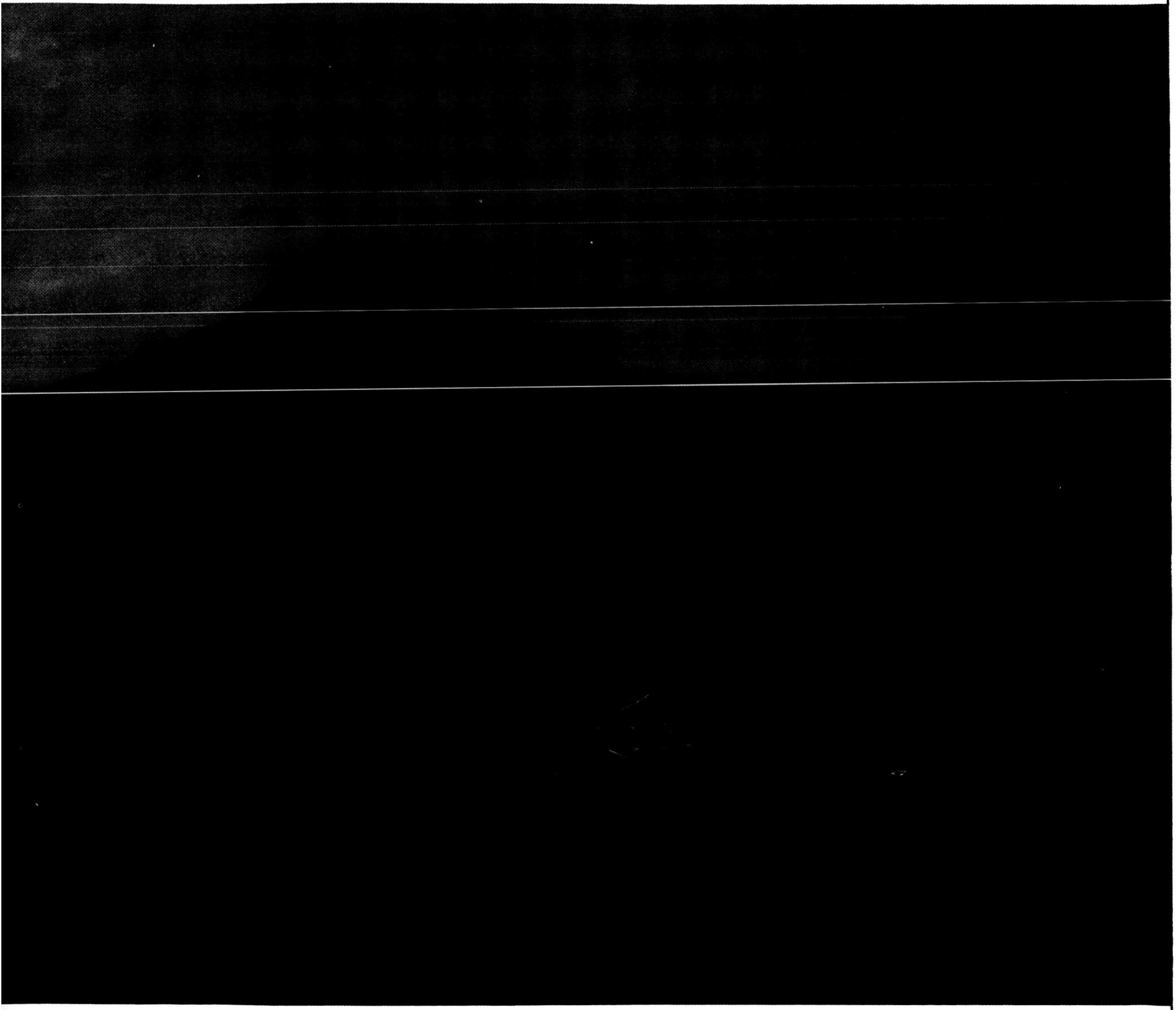
Designing a rover to operate in the martian environment is a formidable task. Mars is much further from Earth than the Moon, and signals can take more than 25 minutes to make a one-way trip (as opposed to one and one-half seconds for Earth-Moon communications). An important feature in the design will be a high degree of autonomous operation, because hands-on "driving" of the rover under those conditions will be impossible. Other essential design features are energy efficiency, slope climbing capability, ease of stowage, ability to negotiate obstacles, good ride quality, and



maneuverability.

Both the LRV and the ELMS can satisfactorily negotiate slopes of up to 30 degrees on relatively soft material and in a variety of other terrains. Walkers, on the other hand, may be able to reach more sites and to negotiate certain terrains better. The main disadvantages of walkers, at this stage, are that their programming is inherently more complicated, and their systems control will need more development time than the other two

An autonomous rover traverses Mars.



possibilities.

For any roving vehicle, a system of artificial three-dimensional vision is needed so that the operators and scientists on Earth can have both knowledge of its surroundings and limited control over its movements. One simple concept would use a pair of video cameras spaced about 0.5 meters apart, which would generate a depth-of-field perception of more than 200 meters. Graphic overlays could then be used to plot a short traverse for the rover out to the limits of its cameras' fields of view, at which point the scene would be surveyed again and the process repeated. Such hands-on control would prevent the rover from traversing terrain too hazardous for it to handle and would simplify the decision-making programming required for its operation.

scientifically valuable samples can be returned in a single payload.

These same operations will also be essential for *all* sample return missions, even those that lie further in the future. The techniques to carry them out on Mars or on a comet nucleus, once developed, will then be available to use on the large number of worlds that wait to be sampled–Mercury, Venus, the asteroids, the Galilean satellites, and the moons of even more distant planets.

Keeping in Touch (Communications)

Communications are an essential part of any space mission, and the proposed Augmentation Missions will place severe demands on the capabilities of existing systems for deep-space communications. Both the *Mars Sample Return* and the *Comet Nucleus Sample Return* missions require precise tracking and location of the spacecraft, especially during such critical maneuvers as orbital insertion, orbital separation and rendezvous, and landing. In addition, the use of a roving vehicle on Mars and a sample collecting device on the comet imposes additional requirements–long periods of high-quality TV transmission, large amounts of scientific data, precise surface locations (for the *Mars Sample Return* Rover) and long transmission distances (for the *Comet Nucleus Sample Return* mission).

As the *Viking* and *Voyager* missions have already shown, these goals can be achieved with current communications systems, and they will also be attainable with the systems planned for the near future. Nevertheless, it is important to consider possible advances in communications technology that may come about in the near future, not because they are necessarily essential to the Augmentation Missions, but because they may provide these missions with important benefits–reductions in power and weight requirements, improved spacecraft design and navigation, and more effective collection and return of scientific information.

Current studies at the Jet Propulsion Laboratory have shown that the use of higher communications frequencies than are now employed can provide significant benefits to major space missions in the future. For instance, a shift from the currently-used X-band transmission (8.4 GHz) to Ka-band (32 GHz) could provide significant advantages for the Augmentation Missions. For the same transmitter power, a higher data rate would be possible. (Or, conversely, the currently available data rates could be provided with lower power.) The higher frequencies would provide improved navigational data because they would be less susceptible to the effects of charged particles in Earth's atmosphere, in the ionosphere of Mars, or in the tail or halo regions of a comet.

There is a special advantage in the higher Ka-band frequencies for the Mars Rover: a smaller antenna (about half the diameter needed for X-band transmission) could provide the same data rate for direct communications to Earth. The smaller antenna would ease packing problems on the vehicle and would take up less of the field of view of the Rover science instruments. It would also present less area to the martian winds, thus reducing the tendency of the vehicle to tip or sway while negotiating rough terrain under windy conditions.

Other technology developments, now under way, may make even higher frequencies available for planetary missions in the more distant future. Optical communications systems, based on lasers and small optical telescopes, will permit even more significant reductions in the mass, volume, and power required for communications systems, while providing higher data rates at the same time. Such communications systems could be based on solid-state lasers (about one watt output power) and small (ten-centimeter diameter) optical telescopes. The Space Station will provide a convenient location for an optical communications terminal above Earth's atmosphere, and a laser on the spacecraft can provide rapid and highly precise astrometric tracking of the spacecraft from such Earth-orbiting telescopes.

Development of these generic technologies is now in progress and will continue in the future. As further studies of possible Augmentation Missions are made, the value of these new techniques to these missions should be carefully considered.

Technologies for Post-2000 Missions

Although the period beyond the year 2000 has not been considered in detail by the SSEC, it is already clear that the need for major planetary missions will continue well into the next century. The outer planets will, in the next few years, become an important focus for future major missions as the data from the *Voyager* and *Galileo* missions are obtained and evaluated. At the same time, the inner solar system will continue to offer important opportunities for exploration by such major missions.

A wide range of possible Augmentation Missions for the post-2000 period can be easily identified. In the outer solar system, such undertakings as combined orbiter/probe missions to Uranus and Neptune, a buoyant station or soft lander on Titan, and instrument networks on the Galilean satellites come quickly to mind. The possibilities for the inner solar system are no less diverse and exciting. Mars could be explored by follow-on long-range surface rovers or by more ambitious sample return missions. Venus could be the target for long-lived atmospheric stations or soft landers. Mercury could be reached, and explored in detail, with orbiters and probes. And more sample return missions could be sent to small bodies–asteroids, and other comets.

It is not appropriate for the SSEC to consider what the details of post-2000 planetary exploration should be, beyond noting that this subject should be examined in detail in the near future. However, **it is appropriate to point out that much of the technology needed for ambitious and demanding Augmentation Missions in the next century will take a long time to develop.** It is therefore worthwhile to discuss the general post-2000 technological needs and to indicate areas in which studies and development should be undertaken in the near future.

Many of the needs for post-2000 missions are the same ones already identified for the *Mars Sample Return* and the *Comet Nucleus Sample Return*–improved propulsion, orbital rendezvous and docking, aerocapture and aeromaneuvering, surface rovers, and

Smart Machines: Planetary Explorers of the Future?

The further we send our machines from Earth, the smarter they have to be. Our instructions to them can only travel at the speed of light, and telling a spacecraft in the outer solar system what to do can take as long as three hours. For this reason, during the recent *Voyager 2* encounter of Uranus, the spacecraft had to carry out its preplanned instructions without help; much of the encounter was over before the first data actually reached Earth.

Since *Voyager 2* was launched almost ten years ago, there have been tremendous improvements in computing techniques and robotic operations. The *Galileo* spacecraft, to be launched to Jupiter, is planned to carry out even more of its mission automatically. Future missions, like sample returns, planetary roving vehicles, satellite servicing, and assembly of Space Station components, will be even more complex, and making such operations largely automatic is a major challenge in developing future machines and computers.

The *Mars Sample Return* and *Comet Nucleus Sample Return* missions recommended for the Augmented Program offer unique opportunities and challenges for *Automation and Robotics (A&R)* technologies. The machines we send to these distant bodies must perform complex tasks under possibly perilous conditions without constant human supervision. In the *Mars Sample Return* mission we will expect a Rover, with limited human control, to faultlessly traverse obstacle-laden terrain and steep grades for distances on the order of kilometers; to collect and document scientifically interesting samples; and to return and transfer these samples to a waiting ascent vehicle. Although these are admittedly difficult and complex tasks, they at least occur on the surface of a planet for which we have obtained a substantial knowledge base from previous missions.

The *Comet Nucleus Sample Return (CNSR)* mission, however, will have a spacecraft acquire and return a pristine sample from beneath the surface of a solar system object which we may have never seen before and whose physical structure is imperfectly known, at best. In the current era of the space program, it is no longer practical to plan a series of missions to a single body, such as a comet or asteroid, in order to build the knowledge base necessary to enable progressively more ambitious exploration missions. To take maximum advantage of the limited mission opportunities available, we must be prepared to proceed directly to higher level investigations at initial encounters, as in the case of *CNSR,* and look to *A&R* technology advancements in robotics and machine intelligence to allow us to adapt, *in situ,* to imperfectly known environments and conditions.

The fields of automation and robotics encompass a broad spectrum of ongoing research areas that will help make our future explorers smarter and more capable. Among these are:

Teleoperations/Telerobotics—Teleoperation is employed to maintain continuous human control over a manipulation system or robot operating at a distance and provide visual and/or other sensory feedback to the operator. When distances become large enough to create time delays that make real-time control impossible, as, for example, the case of a Mars Rover, some degree of autonomy must be provided to the robot system. Telerobotics combines teleoperation with semiautonomous robotic systems. Until artificial intelligence techniques provide robots with far greater autonomy than they presently possess, the telerobotics approach will be needed in unmanned planetary missions to carry out functions such as:

- route planning for rover traverses
- obstacle and hazard avoidance
- complex mechanical operations both on the surface and in planetary orbits, e.g., sampling and transfer operations.

Expert Systems—Expert systems are computer programs incorporating a knowledge base and rules of reasoning that enable a computer to guide and advise a user (human or robot) in the manner of a highly trained specialist, i.e., an expert. Such systems can be used to diagnose, identify, explain, interpret, test, and monitor operations. There are clear *in situ* and ground-based applications of such systems in planetary missions which include:

- sample site selection
- sample identification and selection
- task and operations planning, scheduling, and rescheduling
- system diagnosis, fault isolation, maintenance, and repair.

Sensors and Perception–In robotic applications, perception can be defined as the translation of characteristic or relational properties of an object, obtained from sensory inputs, into the information required to perform a robot function. Depending on the function, sensors could range from video cameras (the most commonly employed robot vision sensor), to sensors that measure mechanical, thermal, acoustic, magnetic, chemical, or other properties of an object or environment. Through perception processes which integrate information from different sensors, and with assistance from

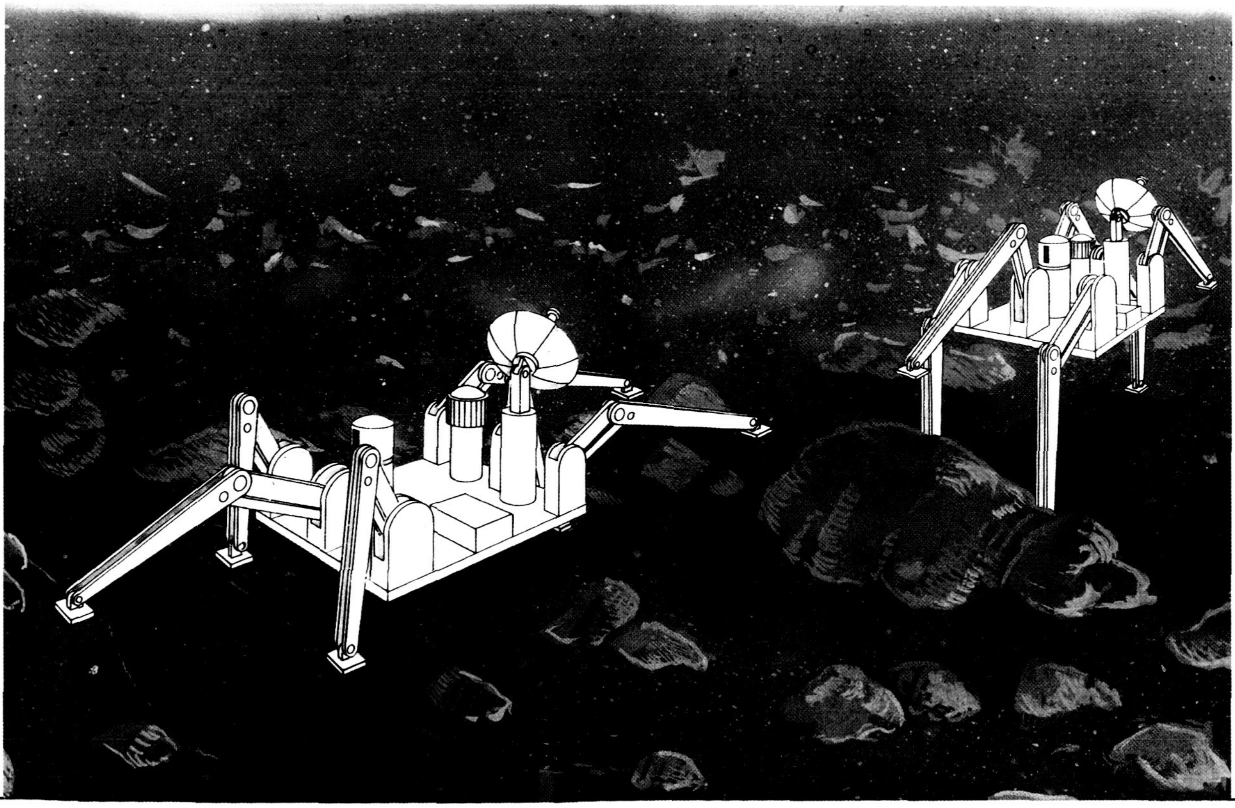
expert systems, future robotic devices may be capable of autonomously performing many of the mission tasks presently felt to require human intervention, such as:
- obstacle avoidance
- sample selection
- complex sampling and manipulation tasks.

Mobility–The research area dealing with robot mobility is one that is particularly critical to space applications. While present-day terrestrial robots are either stationary or operate within a very structured environment, robots in space must be able to operate efficiently in the absence of a gravity reference or in the very unstructured environment of a planetary surface. Current developments in articulated vehicles and legged locomotion hold promise for future use in the Space Station and the *Mars Sample Return* mission.

Autonomy/Artificial Intelligence–To achieve true robot autonomy, it will be necessary to enhance the temporal and spatial reasoning capabilities of these machines through advances in various computer processes comprising elements of what is termed artificial intelligence: logical deduction, probabilistic inference, alternative searching, hypothesis formation, pattern matching, and learning. A robot possessing the ability to reason will be able to:
- interpret and assess new situations from sensory inputs and previous experience
- plan strategies for accomplishing tasks
- automatically execute and monitor tasks
- rapidly replan activities in response to new or unexpected circumstances.

The recommended Augmentation Missions represent the first applications of "smart machines" in planetary exploration. Building upon A&R developments evolving from the Space Station and from other government, university, and private industry studies, planetary missions may be able to take advantage of robots possessing greater autonomy–machines that, without ground control, can traverse unexplored terrain with efficient mobility, detect and avoid obstacles and hazards, identify and collect scientifically interesting samples, and, when encountering unexpected conditions, autonomously plan alternative strategies and operations that will enhance the probability of mission success.

A Mars "walker" negotiates the rugged martian terrain.



sample collection techniques. However, there are many essential needs for Augmentation Missions that cannot be met by technology development focused exclusively on sample returns. These include: nuclear-electric propulsion; improved power systems; long-lived atmospheric probes; hard surface landers and penetrators; spacecraft instruments and components resistant to heat, cold, and radiation; and *in situ* propellant production. In this section we identify and discuss these developments in more detail.

PROPULSION: The increased performance provided by solar-electric propulsion (SEP) is adequate to make the *Comet Nucleus Sample Return* possible. However, SEP cannot be used for missions to the outer solar system because of the inefficiency of solar panels at great distances from the Sun. Development of the related technique of nuclear-electric propulsion (NEP) is needed to provide effective low-thrust propulsion engines for use on future Augmentation Missions to the outer planets and their moons.

POWER: Power for the electrical needs of near-term Augmentation Missions (including SEP for the *Comet Nucleus Sample Return*) can be supplied by currently available technology–solar panels or radioisotope thermoelectric generators (RTGs). These devices, however, are inadequate to provide power for the larger NEP systems needed to propel large and sophisticated spacecraft to the outer planets in reasonable lengths of time. To make the use of NEP practical for major outer planet missions, more powerful space-rated nuclear power systems must be developed at the same time to power large NEP engines.

LONG-LIVED ATMOSPHERIC PROBES: After the first atmospheric probe studies of the outer planets, which will be an important achievement of the Core Program Missions, further exploration will still be needed to understand fully these huge, dense atmospheres. For these next explorations, more capable atmospheric probes will be needed. Two types of future atmospheric probes can be identified. One is a long-lived balloon device (similar to those recently deployed by the U.S.S.R. *VEGA* missions at Venus) which can drift through the upper atmospheres of the outer planets and Titan. The other is a ballistic probe capable of reaching much deeper levels in outer planet atmospheres. Ideally, such a device would be capable of surviving to pressures of about 100 atmospheres (instead of the ten-atmosphere limit for the *Galileo* probe) and would be able to communicate its results from that depth.

These devices do not now exist, and their development will require significant advances in several areas–balloon technology, high-pressure probe technology, and new communications methods for transmitting through the extensive thicknesses of outer planet atmospheres.

HARD SURFACE LANDERS AND PENETRATORS: One of the most effective means for studying a world, whether it is a terrestrial planet like Mars or one of the moons of Jupiter, is the emplacement of a network of shock-resistant scientific instruments which do not need to be soft-landed on the surface. Such a network, whether

it is emplaced as hard landers that remain on the surface or as penetrators which bury themselves, can measure a wide range of critical properties of the planetary surface and interior–earthquake activity, heat flow, chemical composition, atmospheric composition, and local weather.

The *Mars Network Probe*, already included in the Core Program, will provide our first planetary experience with such a network system. Although penetrator technology is well enough developed to be included in the Core Program, continuing study and development will be needed to adapt the technology to the other solid bodies in the solar system.

RESISTANT INSTRUMENT AND SPACECRAFT COMPONENTS: Augmentation Missions beyond 2000 will encounter a range of planetary environments far more severe and far more demanding than those with which we are familiar, and the spacecraft and the instruments they carry will have to function under conditions that no current spacecraft could survive.

Extreme cold, sufficient to produce oceans of liquid nitrogen or hydrocarbons, exists on Titan and on many of the other worlds of the outer solar system. Much closer to home, similar low temperatures are found on the night sides of the Moon and Mercury.

Extreme heat is an equally important hazard. High temperatures (hundreds of degrees Centigrade) are found on the surfaces of Mercury and Venus, and also (somewhat paradoxically) in the outer solar system as well–in the volcanic lakes of Io and in the deep atmospheres of all the outer planets.

Intense charged-particle radiation, frequently at levels lethal to both human beings and current spacecraft, characterizes large regions of the magnetospheres of Jupiter and Saturn and also occurs on the surfaces of moons (like the Galilean satellites) that lie within the planets' radiation belts.

The design and development of a new generation of components for both spacecraft and instruments–cold-resistant, heat-resistant, and especially radiation-resistant–are essential if the most exciting targets for solar system exploration beyond 2000 are to be reached and explored.

***IN SITU* PROPELLANT PRODUCTION:** Sample return missions would benefit greatly if the propellant needed for the return trip to Earth could be manufactured from local materials at the site from which the samples are collected. This exciting possibility has been suggested for the planet Mars, where suitable materials exist in the atmosphere and where the proposed sample return mission is already tightly constrained by the limited capabilities of the *Shuttle/Centaur* launch vehicle.

Such techniques may be inappropriate for the initial *Mars Sample Return* mission, either because the extraction technology is not adequately developed or because its use would involve an unacceptable risk. However, the techniques should be explored further to see whether future sample return missions, to Mars or elsewhere, could benefit by their use. *In situ* propellant production should also be evaluated in the context of a possible manned mission to Mars.

Technologies for Nonterrestrial Resources Use

The technological developments needed for humans to use nonterrestrial resources in space are much greater and more varied than those needed to support an individual planetary mission. Furthermore, such developments will not take place in isolation, for the use of nonterrestrial resources will be an integral part of the much larger context of major human activities in space. The development of technology for resources use will be driven by a larger technological and political commitment to an active and continued human presence in space.

Detailed evaluation of future human activities in space is beyond the consideration of the SSEC. **However, the SSEC recommends that studies be undertaken now, by both the Solar System Exploration Division and other appropriate NASA organizations, to identify and develop the required technologies.** It should be noted that some of the critical technologies required for planetary Augmentation Missions will also support the assessment, extraction, transport, and use of nonterrestrial resources. This potential for dual use makes the development of such technologies as propulsion, aerocapture, and surface rovers even more important and more attractive.

The SSEC's consideration of the future use of nonterrestrial resources has also identified unique technologies required to mine, transport, and extract nonterrestrial resources. Detailed consideration of these technologies, many of them related to the presence of human beings, is beyond the scope of this report. However, the following requirements can be identified as a basis for needed future studies:

- Surface mobility for humans, together with capabilities for scientific and engineering operations to be performed by both humans and machines;
- Surface mining techniques for the lunar surface, asteroids, and the martian surface;
- Extraction technologies involving a variety of possible feedstocks, processes, and products. Possible products include oxygen and metals from lunar surface materials, carbon and hydrogen from asteroids, and propellant from the martian atmosphere or martian surface material;
- Advanced power systems ranging up to 100-kilowatt capacity, both solar and nuclear;
- Fabrication, assembly, and construction techniques applicable to both microgravity and low-gravity environments;
- Improved communications technologies;
- Surface habitations, both lunar and martian.

The Space Station and Augmentation Missions

The SSEC had virtually completed its deliberations on Augmentation Missions in January, 1984, when the national commitment to launch

a Space Station in the early 1990s was announced by President Reagan. Accordingly, it has not been possible for the SSEC to consider in detail the potential of the Space Station for supporting the Augmentation Missions discussed here. **This subject, as well as the more general importance of the Space Station to other types of planetary science activities, should be examined in detail.**

It is important, however, to make some general observations about possible relationships between the Space Station and the Augmentation Missions discussed here.

1. The Augmentation Missions can be carried out independently of the Space Station; the Space Station is not required for their performance. The on-orbit assembly or on-orbit fueling essential for the *Mars Sample Return* can be carried out by the *Space Shuttle* itself. The *Comet Nucleus Sample Return* can be done with a single *Shuttle/Centaur* launch if the required auxiliary propulsion system (e.g., SEP) is developed. Furthermore, the sample return containers for both missions can be retrieved from Earth orbit by the *Space Shuttle* and returned directly to Earth.
2. The required technical developments for Augmentation Missions remain virtually unchanged by the existence of the Space Station. Such requirements as low-thrust propulsion, aerocapture, aeromaneuvering, orbital rendezvous and docking, targeting, surface mobility, and sample collection are still essential.

However, **although the Space Station is not essential to the Augmentation Missions, it has a considerable potential for enhancing them, making their performance more effective, and increasing the scientific yield from them.** Examples of some possible enhancements are:

1. *Increased launch capability.* Operations at the Space Station could increase the launch capability from Earth orbit, thus permitting spacecraft to carry larger payloads, to reach otherwise inaccessible targets, or to enter higher-inclination orbits. A variety of possible operations exists: on-orbit fueling ("topping off") of a *Centaur* launch vehicle, on-orbit assembly of the spacecraft with a fully-fueled *Centaur,* or even the orbital assembly ("clustering") of multiple launch vehicles. A more distant possibility is to use the Orbital Transfer Vehicle (OTV) planned for development as a part of the Space Station complex, as a planetary launch vehicle.
2. *Payload checkout and repair.* The availability of human beings and service facilities in the Space Station will make it possible to conduct prelaunch checks of Augmentation Mission payloads and (to a considerable extent) to service and repair the payloads to correct any problems that are detected. Such capabilities could avoid the necessity of returning a large and complex payload to Earth for repairs and could even correct faults which otherwise would endanger the mission itself.
3. *Sample recovery.* Successful capture of the Earth return capsule, the system that carries a returned planetary sample to Earth

orbit, is an essential part of all sample return missions. As an alternative to orbital recovery by the *Space Shuttle*, followed by direct return to Earth, the capsule could be inserted into an orbit from which it could be recovered by Space Station personnel and returned to the Space Station to await transportation to Earth.

4. *Quarantine and preliminary examination.* The essential preliminary examination and biological assessment of returned samples have previously (as with the *Apollo* lunar samples) been done in special laboratories on Earth. A desirable alternative might be to carry out these studies in a special laboratory on the Space Station, after which the samples could be transported to Earth.

The possible use of the Space Station to support Augmentation Missions must clearly be studied in more detail. **It does not seem desirable at this time to tie the Augmentation Missions rigidly to the Space Station, but each mission should be reexamined to assess the value of the Space Station in carrying it out.**

Instrument Development

The development of new technologies for spacecraft instruments and for ground-based analyses of returned samples is an essential part of future planetary exploration. However, it was felt that the detailed study of such needs was outside the scope of the SSEC's consideration of Augmentation Missions.

Although the Augmentation Missions require the development of several critical technologies to make them possible, they are less closely tied to the development of specific instruments. It could be argued, in fact, that, given the development of the essential mission technologies discussed above, an adequate science yield could be obtained by flying present state-of-the-art instruments on the Augmentation Missions. There are two reasons for this view: (1) even an existing instrument will provide a significant science yield if it can be carried to a new target, such as an unstudied region of Mars or the nucleus of a comet; (2) for sample return missions, the most essential instruments are in terrestrial laboratories, and the importance of the mission lies in bringing the samples back to them.

However, although new instrument developments may not be specifically required for the Augmentation Missions, such developments are important, efficient, and cost-effective. It is far better to carry a current state-of-the-art instrument on a new mission if possible. Instruments to be used in characterizing and documenting selected surface materials for sample return missions would, in particular, benefit from the use of the latest technology advances. It is also important to ensure that the ground-based instruments available to analyze returned samples represent the most current state-of-the-art capabilities.

The investigation of new instrument technologies, and their development for use on planetary missions, should be carried forward as an important adjunct to the Augmentation Missions. It has already been recommended that such developments be supported within the Solar System Exploration Division as an

essential part of the Core Program. The Core Program should also be prepared to identify, and take advantage of, technologies developed for other purposes which are applicable to planetary research.

"...and We'll Do the Job."

The last 25 years of space exploration have been an impressive demonstration of two characteristics considered basic to the human species: curiosity and tool-making. Twenty years ago, the need to travel to the Moon and the planets produced new technologies and new developments (in propulsion, communications, computers, and many other areas) that were needed to make the trips possible. These new technologies, in their turn, made possible a series of voyages, by both human beings and robot spacecraft, that have yielded an unbelievable return in scientific discovery, human excitement, and a clearer understanding of the nature of our immediate cosmic neighborhood.

This basic tie between curiosity, tools, and new knowledge has not been changed by the events of the past generation. Today our curiosity about the solar system is even greater than before, and now even newer tools are needed to satisfy it. Our understanding of the solar system has been raised to a new and higher level, but it is still limited and inadequate. The newly-revealed planets and their moons still contain a host of mysteries, and the techniques and the equipment of today are no longer adequate for the detailed explorations that we now need to solve them.

New tools, and the new voyages they can make possible, are both within our reach at this time. We understand fairly well what problems must be solved in order to make possible this new era of planetary exploration. We have some good ideas about possible solutions and how to develop them. The path to these solutions–and to the new and exciting missions of the Augmented Program–is difficult and challenging, but it is not impossible. No new scientific breakthroughs are needed, and much of the development involves only learning to build better what we have already learned to build well. We can start now to mark the end of the 20th Century by building the technical framework for a new era of intense, active exploration of the solar system that will extend into the decades–and perhaps even the centuries–beyond.

CONCLUSIONS

1. None of the Augmentation Missions considered here can be done with existing technology. To make any Augmentation Mission possible, new techniques must be developed in a variety of fields.

2. The need for new technology development is regarded as one of the positive features of the Augmented Program. If the previous history of space exploration is any guide, then the technologies developed for the Augmentation Missions will provide major benefits in other areas and even outside the space program itself.

3. Required technological developments are identified in detail only for the two sample return missions (the *Mars Sample Return* and the *Comet Nucleus Sample Return*) discussed in detail in this report. Technology developments considered essential for these missions include: improved propulsion capabilities, aerocapture, aeromaneuvering, automated rendezvous and docking, automated surface mobility (i.e., rovers), and automated sample collection and handling. Improved communications, while not essential, could be highly beneficial. Many of these technologies are generic; their development for sample return missions will also support other Augmentation Missions in the more distant future.

RECOMMENDATIONS

1. The development of technologies critical to the *Mars Sample Return* and *Comet Nucleus Sample Return* missions should be undertaken in the near future. These technologies include: improved launch and propulsion capabilities, aerocapture, aeromaneuvering, automated rendezvous and docking, automated surface mobility, and automated sample collection and handling. Because many of these technologies are generic, their study and development may fall outside the scope of the Solar System Exploration Division. In these cases, the Division should ensure that detailed mission requirements are made available to the appropriate organizations and that the final form of the developed technology is compatible with the sample return missions.

2. Critical long-lead-time technological developments required for Augmentation Missions in the post-2000 period (especially missions to the outer planets) should be identified now in order to ensure their availability. Specific technical needs, that will not be met by developments focused on the sample return missions are: improved propulsion (nuclear-electric), power, long-lived atmospheric probes, hard surface landers and penetrators, spacecraft instruments and components resistant to a variety of extreme conditions (heat, cold, radiation), and *in situ* propellant production.

3. A special class of technological developments is required to support the use of near-Earth nonterrestrial resources in major space undertakings. Although much of the required development will be done in the context of major manned space undertakings that are beyond the scope of this report, the necessary technologies should be identified in sufficient detail to ensure that they are included in the appropriate studies and plans. Some of the necessary technological developments needed for the assessment, transport, processing, and use of nonterrestrial resources parallel developments required for the Augmentation Missions, e.g., improved propulsion, aerocapture, and automated surface mobility. Other essential technologies not addressed by the Augmentation Missions include: surface mobility for human beings on the lunar surface or on asteroids, surface excavation mining techniques, extraction technologies, advanced power systems, fabrication and construction techniques, surface habitation technology, and improved communication methods.

4. The use of the Space Station to augment and enhance the Augmentation Missions considered in this report should be studied in detail immediately. Although the Space Station is not essential for the Augmentation Missions, it can provide important support through a number of capabilities, including: increased launch capability, payload checkout and repair, sample recovery, and sample quarantine and preliminary examination.

5. Development of new spacecraft instrumentation, although not a basic part of the Augmentation Missions, should continue to be supported in order to ensure that the Augmentation Missions have available the state-of-the-art scientific instrumentation to maximize the scientific return.

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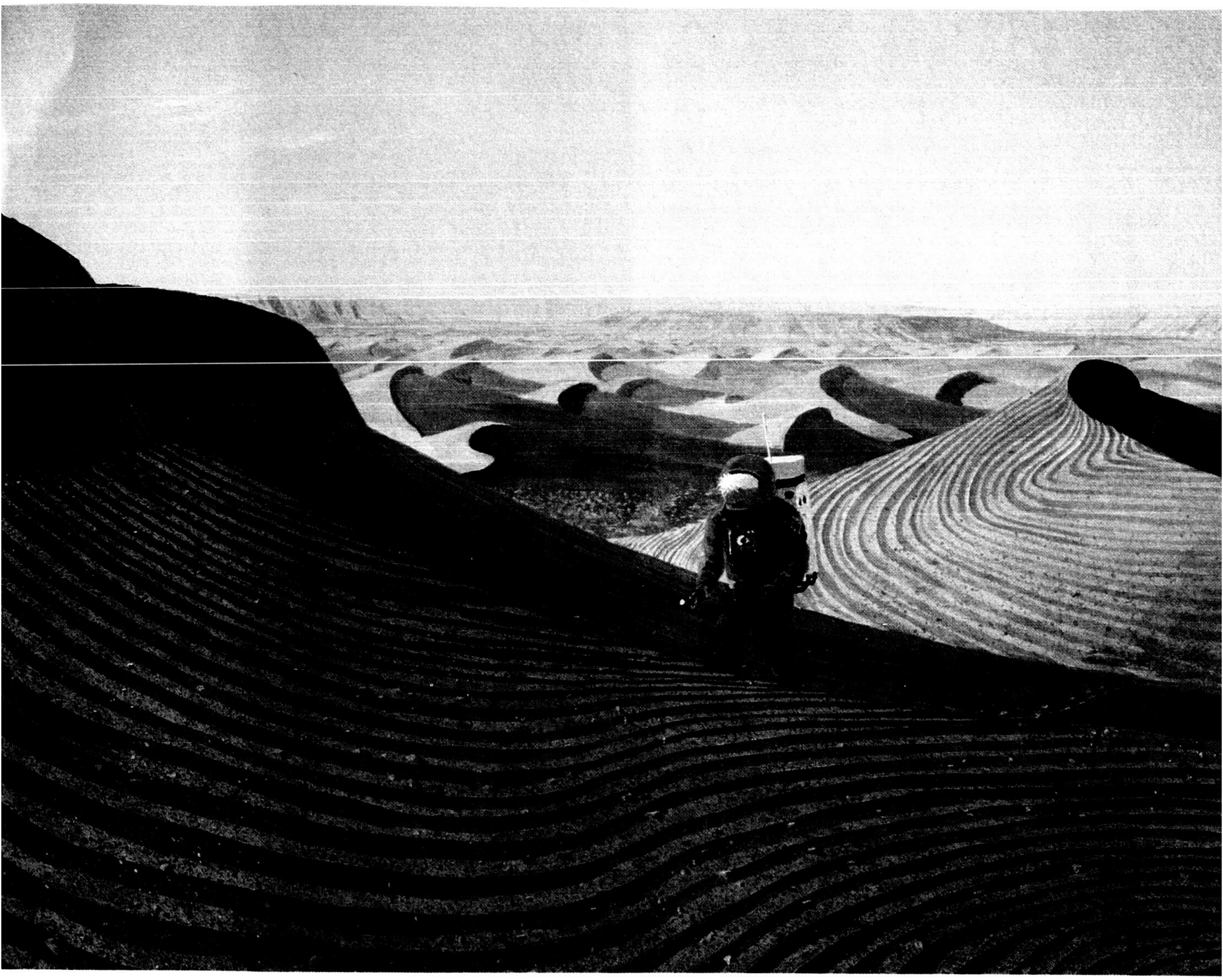
116, 117 . . . *Comet Nucleus Sample Return* Spacecraft (drawing): Stephen Hoffman, SAIC
120 . . . Comet Surface (painting): William K. Hartmann
132 . . . Neptune Probe (painting): Ron Miller
136 . . . Uranus: JPL/NASA
142 . . . *Pluto Flyby* (painting): Ron Miller
144 . . . Titan (painting): Ludek Pesek, © National Geographic Society
146 . . . Saturn Ring Rover (painting): Ron Miller
155 . . . Asteroid Towing (painting): William K. Hartmann
157 . . . Earth-Approaching Asteroid (painting): William K. Hartmann
160 . . . Interim Lunar Base (painting): Pat Rawlings, Eagle Engineering
164 . . . Impact Pit on *Solar Maximum Mission* Satellite: Johnson Space Center/NASA
172 . . . Post-*Apollo* Lunar Expedition (painting): Ron Miller
178 . . . Asteroid Mining (painting): © Pamela Lee
190 . . . Beta Pictoris: NASA
192 . . . Planets in Nebulosity (painting): William K. Hartmann
196, 197 . . . Milky Way Galaxy: JPL/NASA
200 . . . Thaw Refractor (photograph): © Herbert K. Barnett
202 . . . Astrometric Telescope Facility: NASA
214 . . . Nuclear-Electric Propulsion (painting): JPL/NASA

Manned Mars exploration: the next "giant leap for mankind." An astronaut explores the vast sand dunes on Mars.



219 . . . Aerocapture (painting): William K. Hartmann
222, 223 . . . Rover Traversing Mars (painting): Ron Miller
227 . . . Walker Concept: NASA
239 . . . Manned Mars Exploration (painting): William K. Hartmann

All diagrams in Chapter 3 . . . (pages 76, 77, 85, 86, 88, 89, 92, 93, and 94): JPL/NASA